A Fresh Start for Flood Estimation in Ungauged Catchments

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Existing Methods for Flood Estimation in Ungauged Basins have High Uncertainty

- In the UK, the most accurate methods have a Factorial Standard Error around 1.4-1.5, i.e. 95% prediction interval is Q/FSE^2 to $Q*FSE^2$

Journal of Flood Risk Management — CIWEM

How reliable are design flood estimates in the UK?

T.R. Kjeldsen

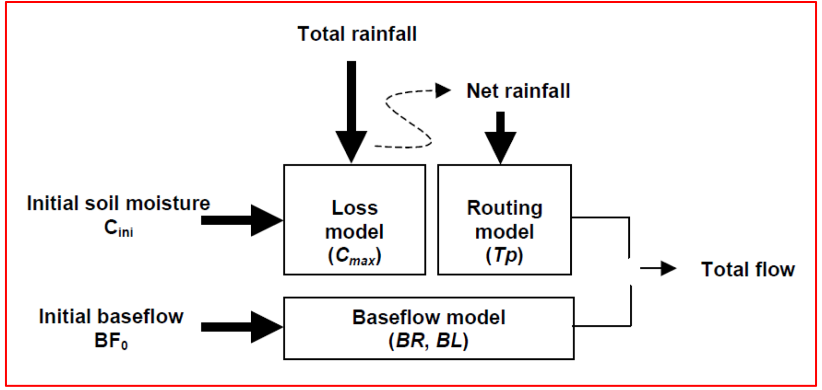
- In practice, these uncertainty bounds are approximately a factor of 2! That's too much!!!

- In many other countries, the errors are even larger than in UK
    - UK hydrology is relatively uniform in space, it has a dense gauging network, relatively long records, and a rich history of research on the topic
- What can we do to reduce the uncertainty?

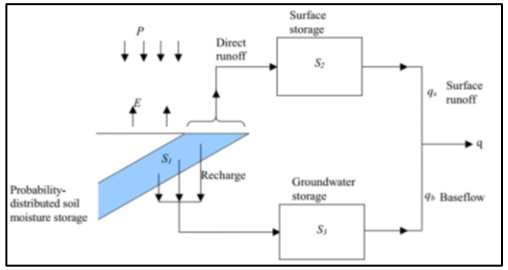
How to Proceed? Options?

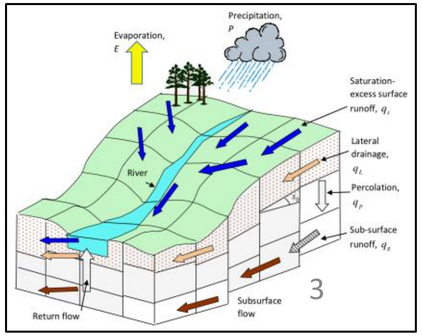
$$\ln QMED = 2.1170 + 0.8510 \ln[AREA] + 1.8734 \left[\frac{1000}{SAAR}\right] + 3.4451 \ln[FARL] - 3.080 BFIHOST^2$$

- Refinement of existing standard methods
  - Regionalisation methods
  - Rainfall-runoff methods
  - For ungauged catchments, both of these rely on using multiple regression



- Continuous simulation
  - Spatially lumped or distributed models
  - Estimation of model parameters for ungauged basins remains challenging
  - Even correct specification of model structure is tricky!
- Or maybe something different???

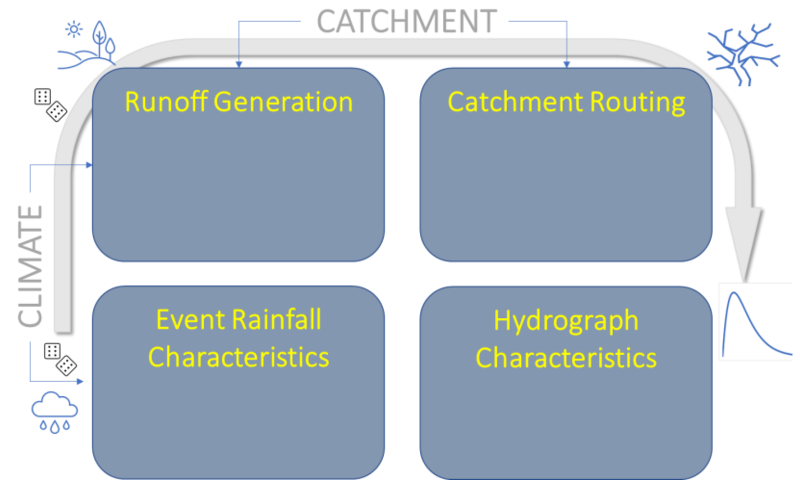




Event-Scale Derived Distribution Method

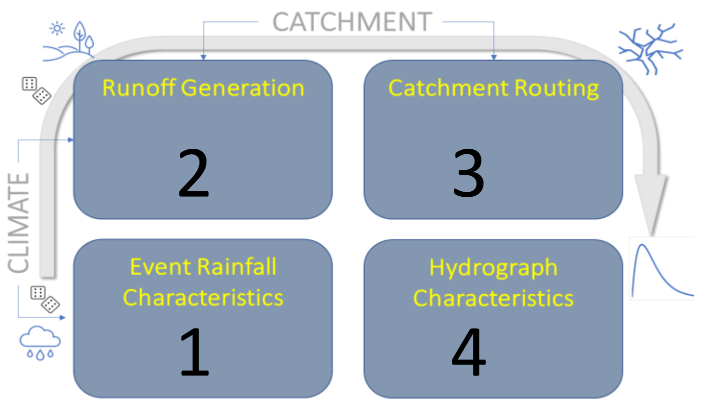
- Probability distributions of rainfall, initial conditions, baseflow and model parameters are transformed into probability distributions of flood events

Probability distributions of rainfall, initial conditions, baseflow and model parameters → "Model" → Probability distributions of streamflow events → Frequency analysis → Probability distributions of extreme events



Why make a Model like this?

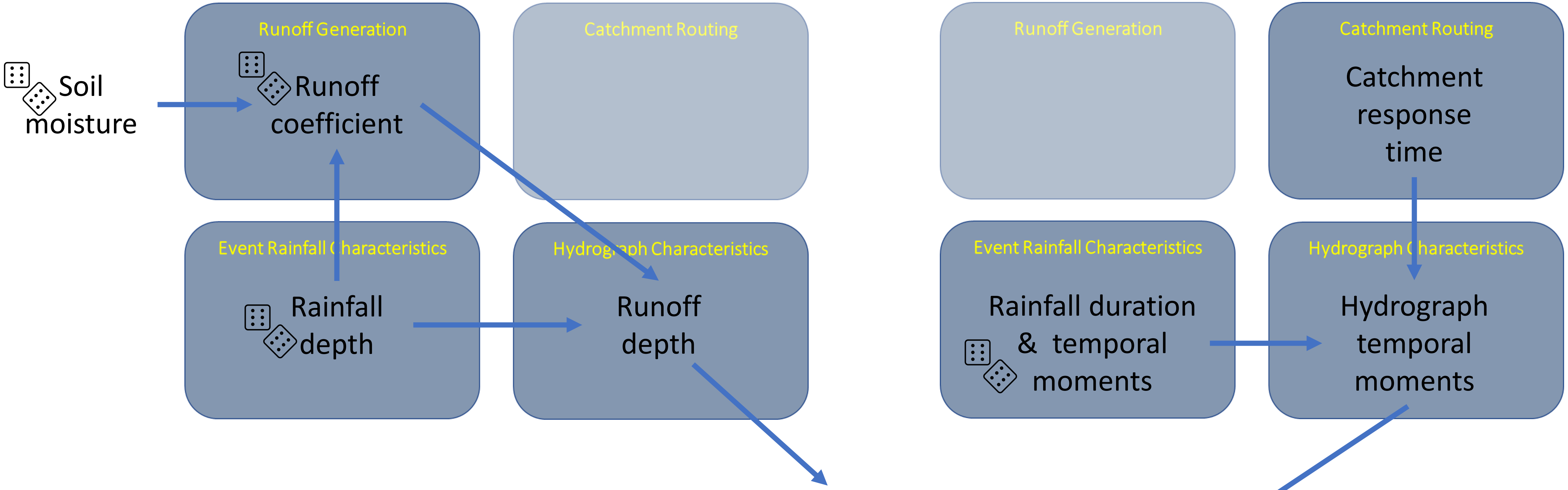
- Improved use of hydrological knowledge in flood estimation
- Lots of data: we use 300,000 events from ~500 catchments
- How does a flood peak get "made"? (the Model)
    1. It rains (random seasonal process, distributed in time and across the catchment)
    2. How much rain runs off? (depends on antecedent soil moisture, catchment properties)
    3. That runoff volume is spread over a certain amount of time
    4. The less it spreads out in time, the higher the peak flow



- We break the flood down into these stages, and predict each separately, to help check the method is making sense.
- We can see where the uncertainty in estimates comes from

Event-Scale Derived Distribution Method

- The Model conceptualisation is non-standard modelling, but it's *mostly* standard hydrology thinking

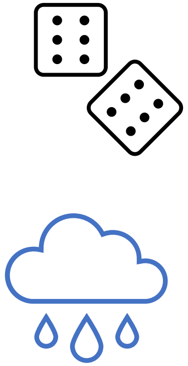


$$Q_{Peak} \approx \frac{Runoff\ Depth}{\sqrt{2nd\ Temporal\ moment}}$$

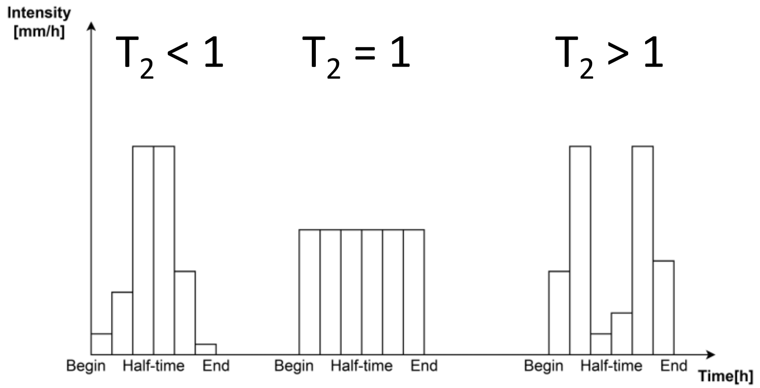
Viglione et al (2010)

1. Rainfall
Stochastic Model for

Intensity & Duration
Temporal Moments
Spatial Moments
(Roberto Quaglia)

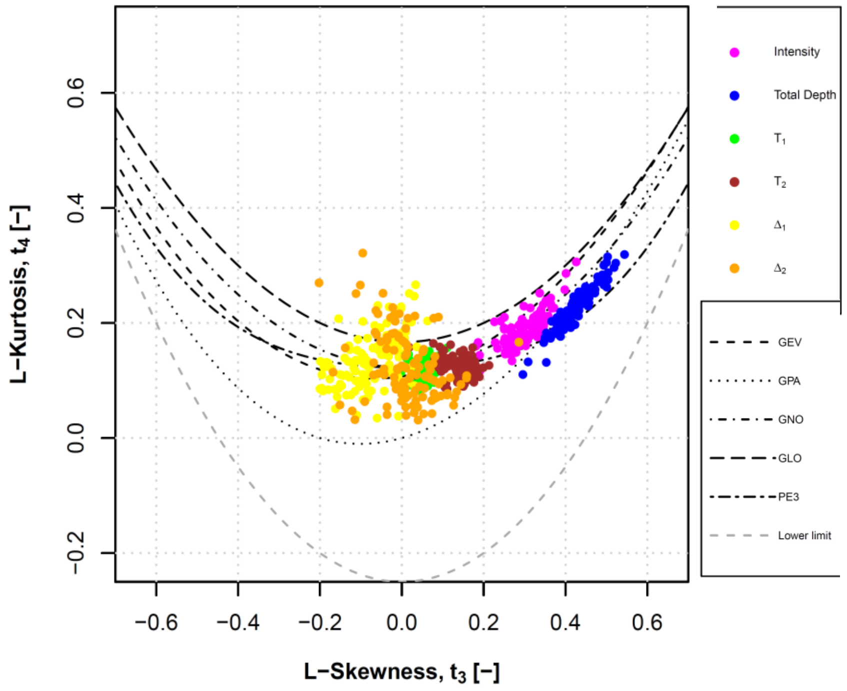


Temporal moment T_2 quantifies spread of rainfall



- Study a large sample of events
- Expand the typical stochastic description of rainfall to make a joint distribution of Depth, Intensity (or Duration), Temporal and Spatial Moments
- Identify marginal distribution families for each variable, and use Vine Copula to link them

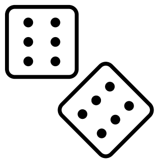
Distributions for Rainfall Characteristics

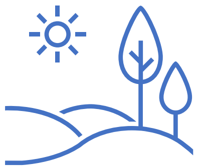


We do not address spatial variability in detail because
(i) more work is needed on hourly spatial rainfall
(ii) Giani et al (2022a) show many UK events are ~uniform

2 . Runoff Generation
Stochastic Model for
Event Runoff Coefficient

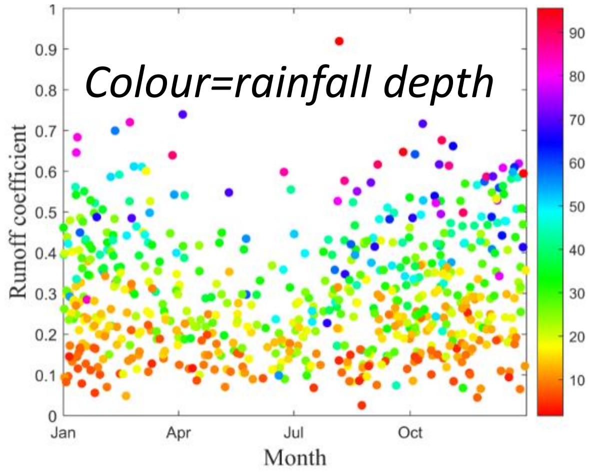
conditioned by soil moisture &
rainfall event characteristics
(Yanchen Zheng)



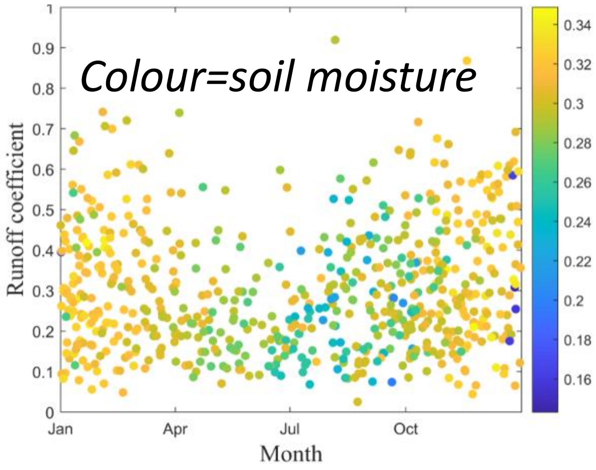


Data analysis shows higher runoff coefficient for:

higher rainfall

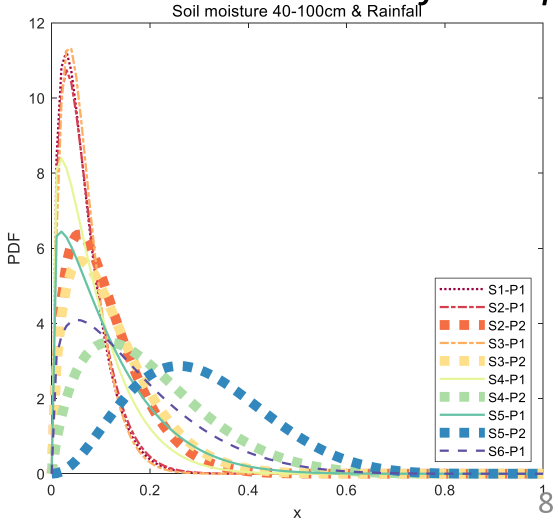


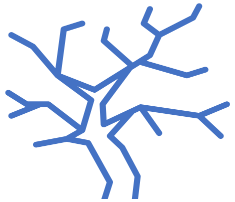
higher soil moisture



- Study a large sample of events
- Runoff coefficient = Event runoff / Event rainfall
- Runoff coefficient varies systematically with both soil moisture and event rainfall depth
- Fitted a beta distribution (range 0-1) whose parameters depend on soil moisture and event rainfall depth
- Developing a strategy for estimating these distributions in ungauged catchments
- For more details, see Zheng et al (2023a, 2023b)

pdfs of runoff coefficient as function of soil moisture and rainfall depth



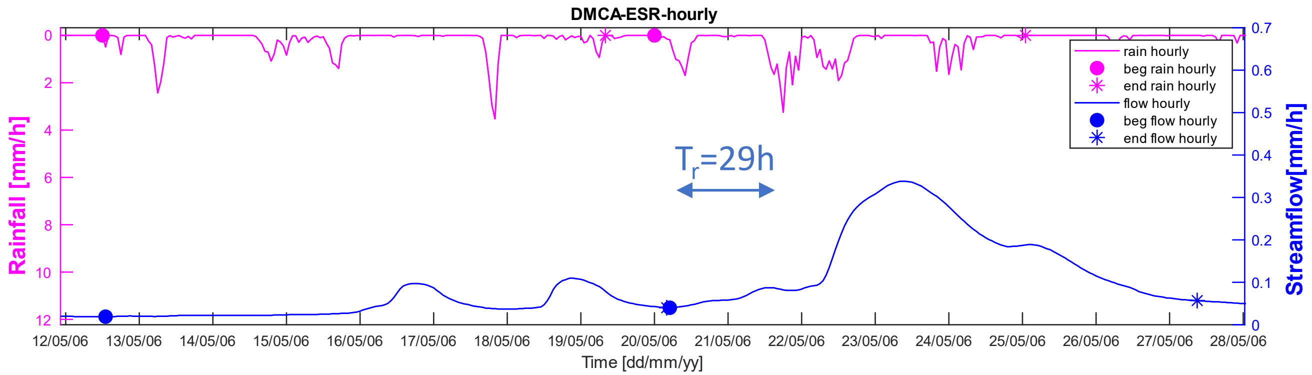


3a. Catchment Routing

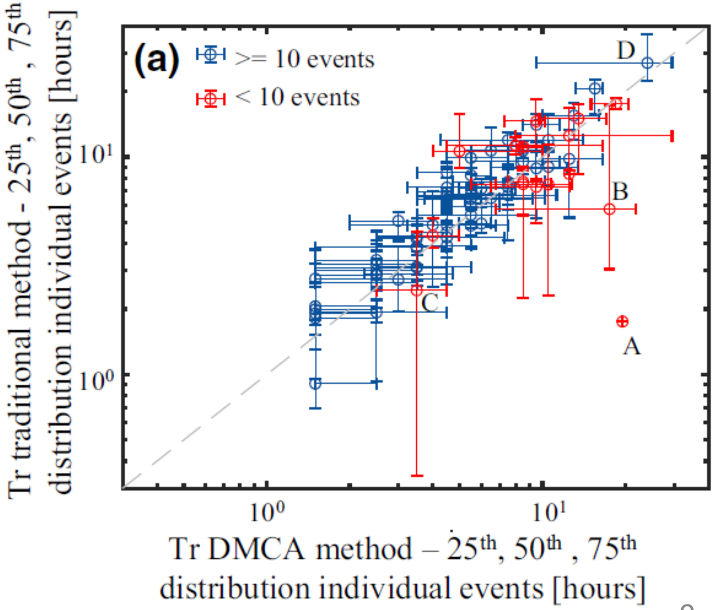
What is
Catchment Response Time?

(Giulia Giani)

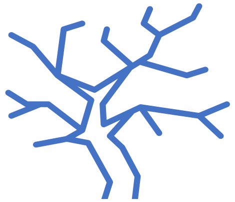
- Developed new DMCA method for assessing Tr catchment response time from rainfall-runoff data (see Giani et al 2020)



- Automated, objective, no parameters to set
- Doesn't require baseflow separation
- Results are consistent with standard methods
- Can be applied to full time series, or to events



Python and Matlab code available at https://github.com/giuliagiani/Tr_DMCA



3b. Catchment Routing

Automated event identification

(Giulia Giani)

New automated event identification method

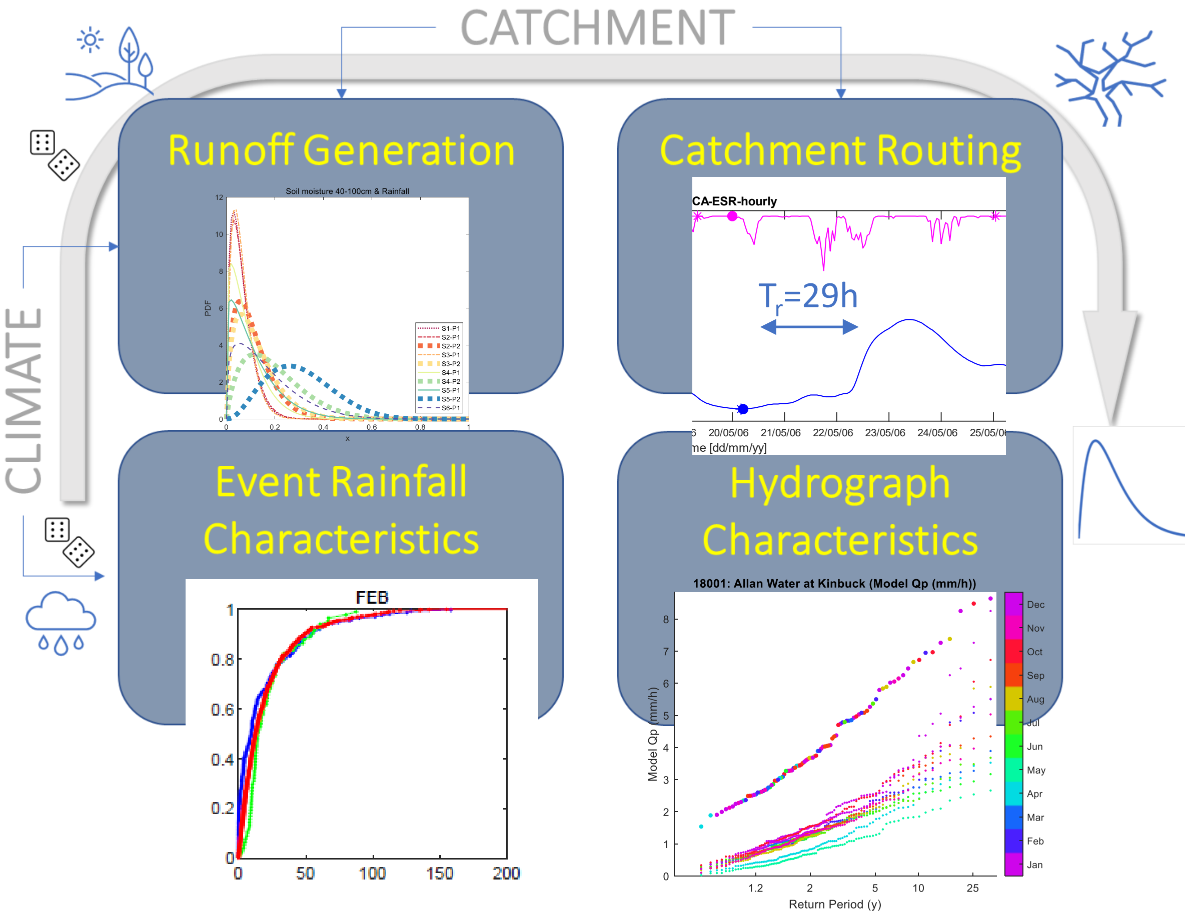
- Depends on Tr, catchment response time
- Uses the DMCA time series analysis, per event
- No subjective choices
- No need for baseflow separation

- Enables us to identify large samples of events for hundreds of catchments, without tuning
- Requires a timestep fine enough to resolve the response

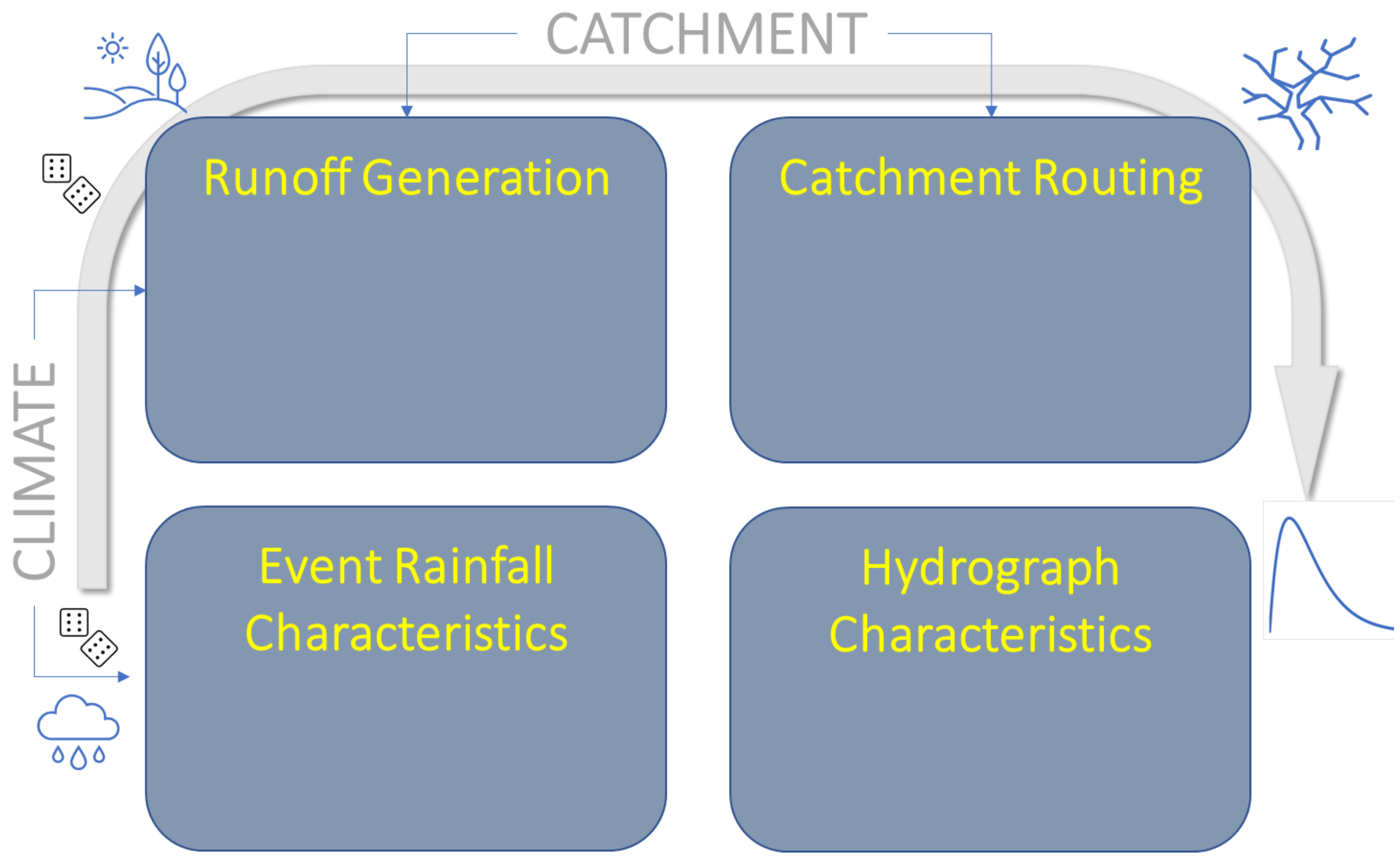
Giani et al (2022b), "An objective time-series-analysis method for rainfall-runoff event identification"
Code available at https://github.com/giuliagiani/DMCA-ESR

Summary

- New method for flood estimation, breaks floods into testable stages
- Progress on
  - rainfall characterisation
  - runoff coefficients
  - catchment response time
  - event identification
- We have linked these elements to implement derived flood frequency as software
- We are beginning the testing
- Still much to do



Thank You for Listening!



References

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- Viglione et al (2010) https://www.sciencedirect.com/science/article/abs/pii/S0022169410003264
- Woods and Sivapalan (1999) https://agupubs.onlinelibrary.wiley.com/doi/10.1029/1999WR900014
- Zheng et al (2023a) https://doi.org/10.1029/2022WR033226
- Zheng et al (2023b) https://doi.org/10.1029/2022WR033227

ADDITIONAL SLIDES …

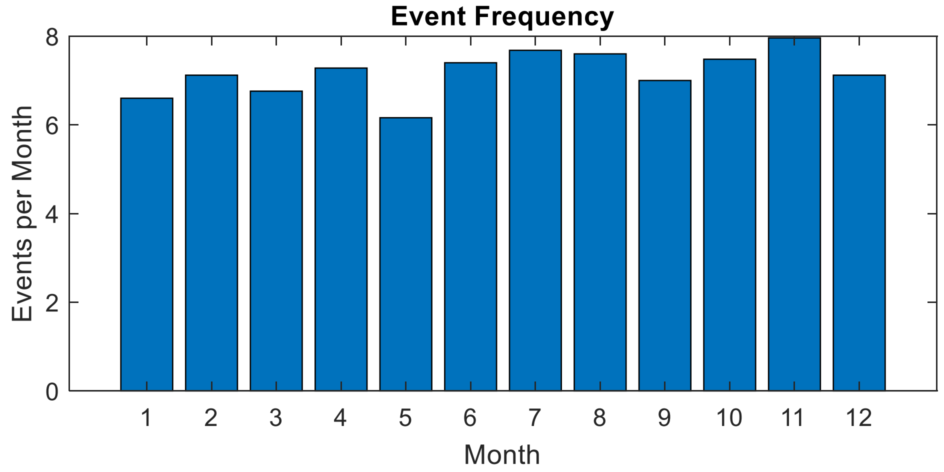
Unsolved Problems and Questions

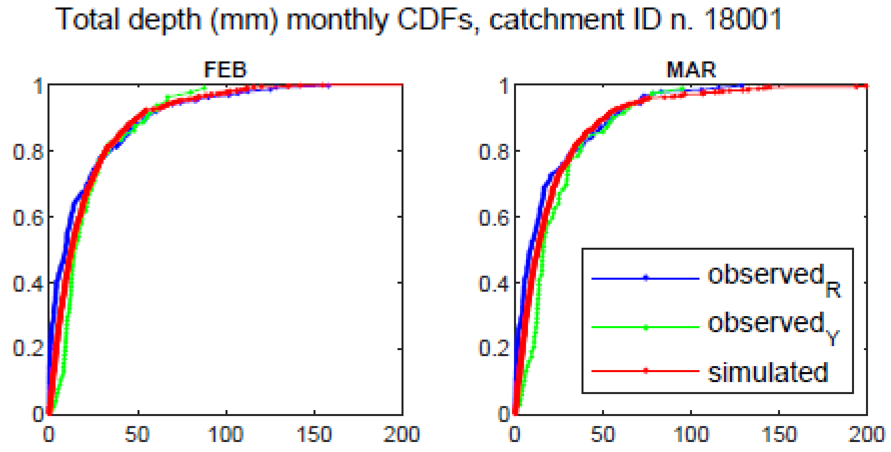
- Estimation of Catchment Response Time in ungauged UK catchments (Giulia Evangelista & Pierluigi Claps: https://meetingorganizer.copernicus.org/EGU24/EGU24-1038.html)
- Physical interpretation of Catchment Response Time (Yiming Yin had a poster yesterday: https://meetingorganizer.copernicus.org/EGU24/EGU24-4177.html)
- Could the approach could be adapted to other flood regimes?
  - Use understanding of processes controlling flood occurrence/magnitude
  - Infiltration excess, snowmelt, …
  - What triggers an event? What controls its magnitude?

Temporary Solutions

- This is a big problem and not every step can be fully solved now
- We tolerate empirical relationships, as stop-gap solutions, e.g.
  - How does soil moisture status affect event runoff coefficient?
  - How does rainfall event depth affect event runoff coefficient?
  - What is catchment response time of ungauged catchments?
- To prioritise solutions of unsolved problems, use sensitivity analysis, e.g.
  - How much uncertainty in the estimate of median annual flood is caused by the uncertain estimate of catchment response time?
- How will we get to flood peaks? See Figure 11 of Viglione at el (2010)

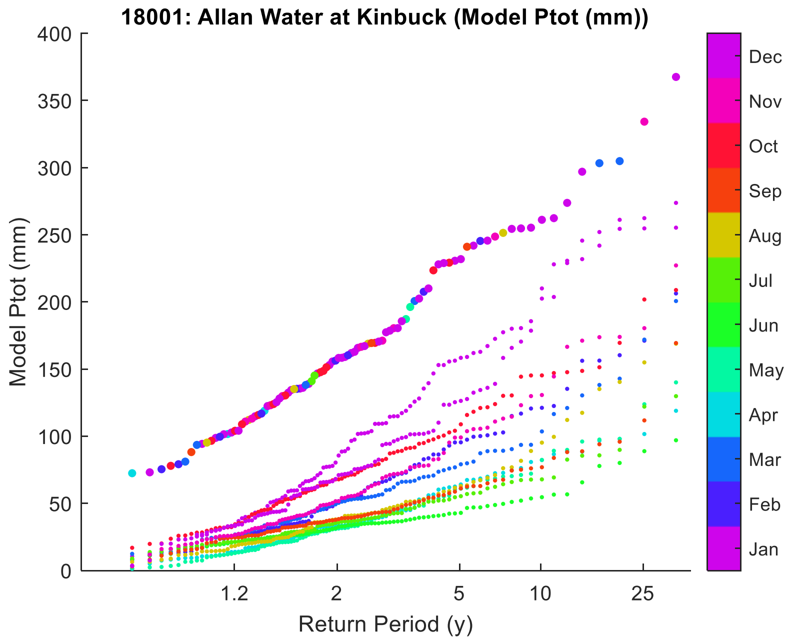
Rainfall - example





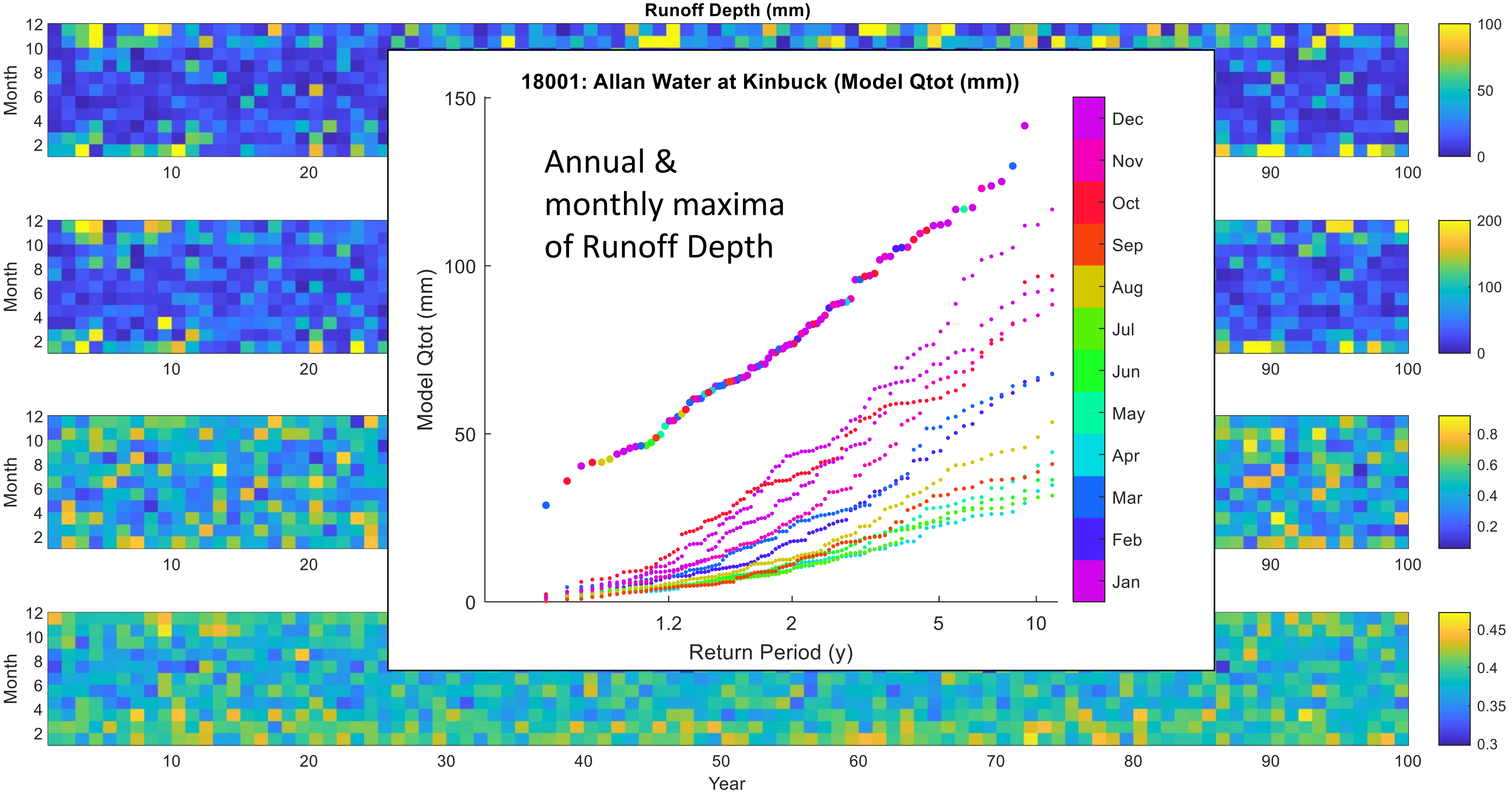
Marginal distbn of Depth, by month

- Sample 100 years from joint pdf of Depth, Intensity, Temporal and Spatial Moments
- Multiply Depth by runoff coefficient
- Use Duration and moments later …



Annual & monthly maxima of Rainfall Depth

Runoff Coefficient and Rainfall - example



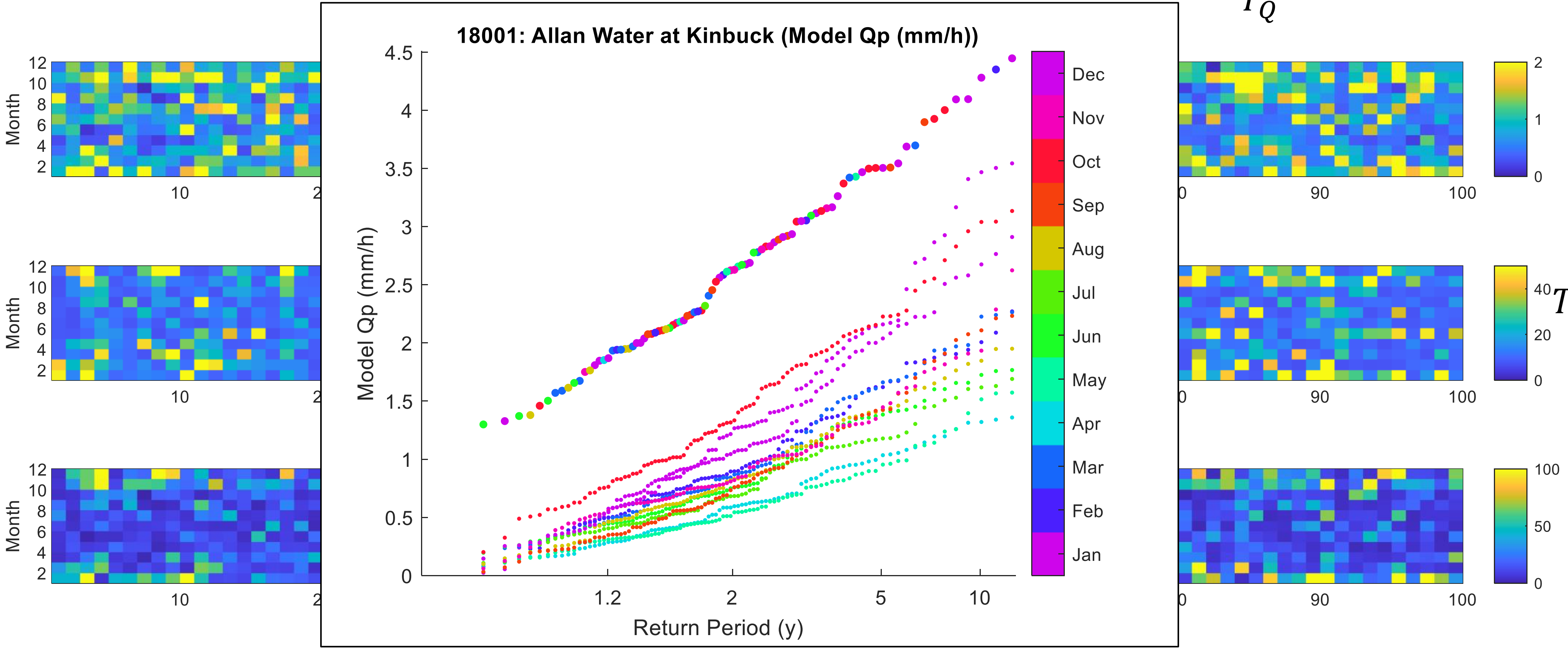
Runoff = Rain * Runoff coefficient

Runoff coefficient from pdf conditional on Rainfall and Soil moisture

(Images only show the largest runoff event of each month)

Runoff Peak - example

$$Q_{Peak} = \frac{Runoff\ Depth}{T_Q}$$

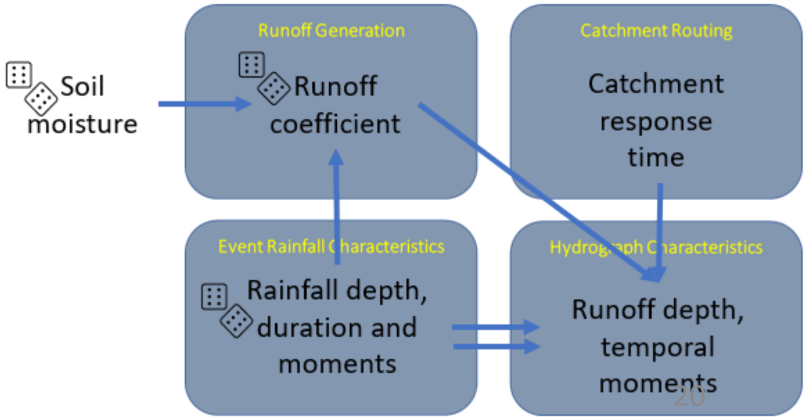


$$T_Q^2 = T_P^2 + T_r^2$$

(Images only show the largest peak runoff event of each month)

Features of this Approach

- Advantages
  - Generic approach, can be adapted to other dominant processes (if understood)
  - Uses knowledge of hydrological processes
  - Explicit recognition of seasonality, nonlinearity, spatial and temporal variability
  - Modular approach with simple components, can debug/improve at multiple points
  - Multiple responses to evaluate (runoff coefficient, runoff volume, hydrograph timing, flood peak, both monthly and annual extremes)
  - Explicit links to climate at multiple timescales
- Disadvantages
  - Requires knowledge of hydrological processes
  - High information needs
  - Not suitable for spreadsheet implementation
  - How to explain interconnections of model components



What's Next?

- Flood peaks
  - Assess effectiveness of T_Q as an event timescale
  - Quantify ability to estimate median annual maximum flood
- Process chain
  - Sensitivity analysis to see where using estimated values in place of at-site values degrades performance the most
  - Implement spatial moments of rainfall when suitable data are available
- Gradually replace empirical relationships:
  - How much does catchment response time Tr vary between events, and why?
  - What is the process explanation for the links between soil moisture, rainfall depth and event runoff coefficient?

What about Spatial Moments?

- Giani et al found that spatial rainfall moments are relevant for ~10% of UK rainfall-runoff events, mainly on larger catchments
- Empirical evidence shows that in those cases, spatial moments contain information about both the timing and peakedness of hydrograph response
- Study of the probability distribution of spatial moments based on the CEH-GEAR1h data indicated a surprising number of outliers
- Perhaps revisit the spatial interpolation method used for CEH-GEAR1h
- At this stage we have chosen to focus on events which are close to spatially centered and uniform

How to get to Annual Exceedance Probability?

- Standard methods for this are described in Sivapalan et al (2005)
  - In brief, a Monte Carlo integration:
    - Generate N events per month, compute flow, note the largest flow in the month
    - Develop a frequency curve for maximum flow in a month
    - Combine monthly frequency curves to get annual maximum
- Alternatively, analyse the entire sample of events of all sizes, using Metastatistical Extreme Value Distribution (e.g. Miniussi et al 2020)

What about Baseflow?

- We have a separate pdf for baseflow, varying by month, lognormally distributed
- Eventually this pdf will be conditional on soil moisture
- Have not started on estimating baseflow pdf in ungauged catchments, but previous UK research on BFI using HOST soil characteristics suggests that this is feasible.
- See also Gnann et al (2020, Fig 6) which shows that a combination of climate and presence of fractured aquifers explains the seasonal amplitude and phase of UK streamflow