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Investigation of marginal distribution and dependence structure of simulated streamflow by a rainfall-runoff model

Vasileios Kourakos, Theano Iliopoulou, Panayiotis Dimitriadis,
Demetris Koutsoyiannis, Vassilios Kaleris, and Andreas Langousis

Department of Water Resources and Environmental Engineering
National Technical University of Athens
Greece

Abstract

- The aim of this work is the investigation of how rainfall-runoff models preserve the stochastic characteristics of real-world streamflow data. Furthermore, it also deemed useful to compare the stochastic properties of output with those of input processes (rainfall), with focus on marginal distribution tails and long-term persistence.
- For this purpose, a case study will be performed using the ENNS rainfall-runoff model, and for all processes will be studied the marginal distributions and the dependence structures.

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CAMELS Data Set & Basin Selection Process

- This research was performed by using **C**atchment **A**ttributes and **ME**teorology for **L**argesample **S**tudies (**CAMELS**) data set (Newman *et al.*, 2014), which includes **671 catchments** and provides :
  - basic metadata, such as basins boundaries, their location, size, mean elevation and slope
  - observed daily stream flow records at the outlet of each catchment
  - daily time series of spatially averaged precipitation, maximum, minimum and mean temperatures, shortwave downward radiation, day length, humidity, and snow water equivalent.
- A combination of criteria was taken into account for the selection of the study area. Specifically, the optimal area resulted from :
  - the percentage of stream flow missing values and
  - cross-correlation between rainfall and streamflow for lag 0.
- The study area eventually chosen is located in **Queets River near Clearwater**, in the state of Washington.
- The data set for this basin includes 34 hydrological years, from 1980/81 to 2013/14.

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Catchment Physical Attributes & Mean Annual Characteristics

- Area : 1155.71 km^2
- Mean Elevation : 437.01 m
- Mean Slope : 96.58 m/km
- Mean Runoff : 9.680 mm/d
- Mean Precipitation : 8.865 mm/d
- Mean Potential Evapotranspiration : 1.892 mm/d
- Mean Temperature : 8.137 °C

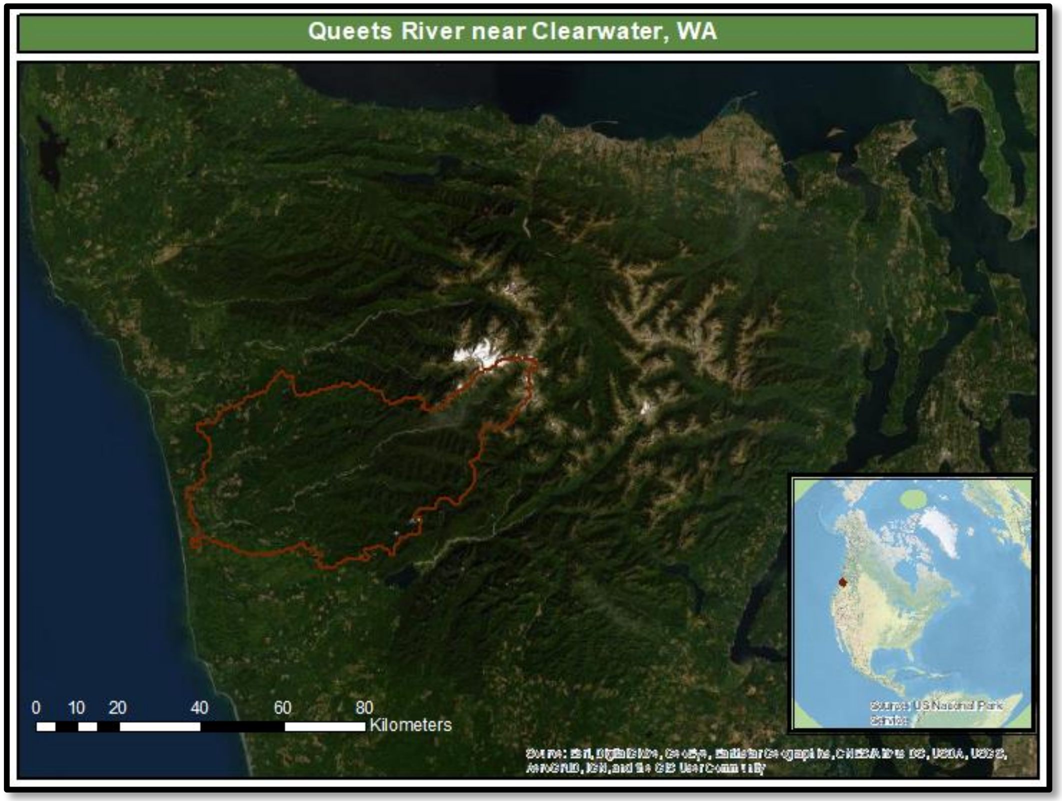

Figure 1. Studied River Catchment

Precipitation and Runoff Data (I)

- As can been noticed from the previously mentioned mean annual characteristics of the basin, **runoff exceeds precipitation**, on average.
- It is also evident from the following figure that after the first decade of the available data set, measured annual runoff surpasses annual basin-averaged precipitation.

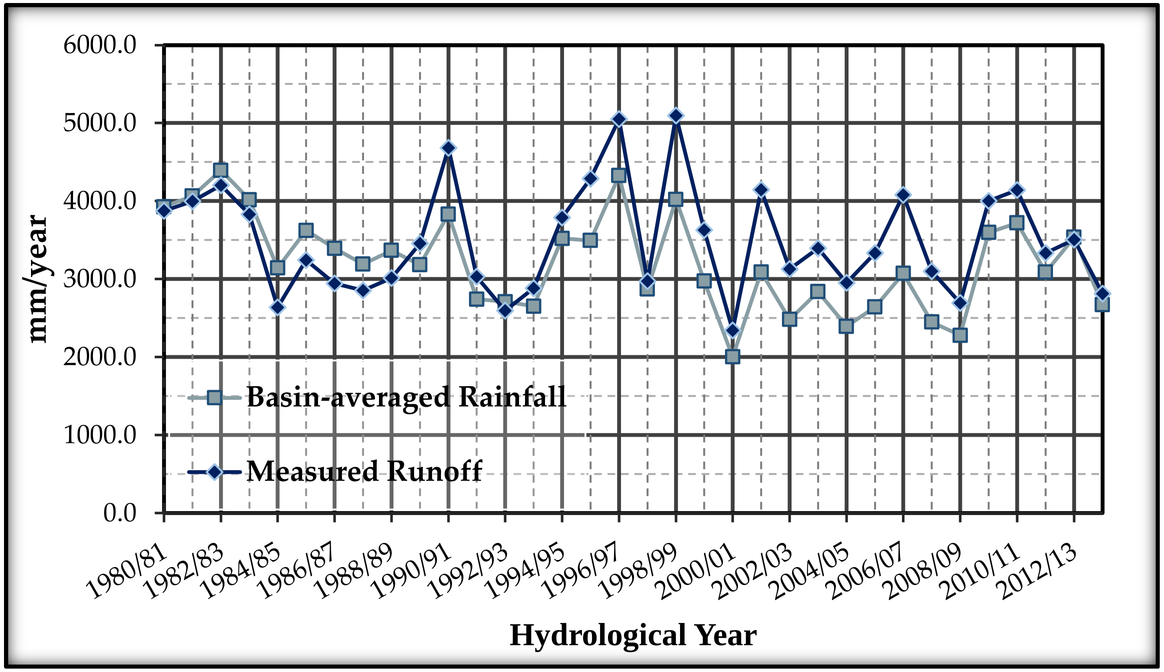

Figure 2. Basin-averaged annual precipitation and measured annual runoff for the period from 1980/81 to 2013/14.

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Precipitation and Runoff Data (II)

- Although it was attempted to detect a conducted research where there is a well-grounded explanation concerning this phenomenon on this specific catchment, there were no findings.
- This problem could be attributed to information related to either measured precipitation data (underestimation of precipitation) or measured streamflow data (overestimation of runoff).
- This natural occurrence could also be associated with underlying hydrological processes, such as glaciers melt. The studied catchment belongs to the Olympic Peninsula, an area currently containing 184 alpine glaciers whose combined area is equal to 30.2 ± 0.95 km^2 (Riedel *et al.*, 2017). According to Riedel *et al.*, the glaciers are in rapid decline based on the records for the past 30 years, and provide the streams of the Olympic Peninsula, with Queets river among them, with significant amounts of water.
- Subsequently, it will be attempted to model measured river runoff, without taking into account the previously cited amounts of water, since the amount of this contribution to river runoff of the studied catchment is unknown to the authors, and then assess the performance of model results, given the distinctiveness of the specific data.

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Hydrological Modelling

- For the purposes of this study, ENNS rainfall-runoff model (Nachtnebel *et al*. 1993) was used to model river runoff in the study catchment. The simulation will be carried out by adopting a **daily time step**, so that it should match the time scale of the input data (precipitation and temperature).
- ENNS is a research-oriented lumped conceptual model developed for the river Enns in Austria, its conceptual structure represented below.

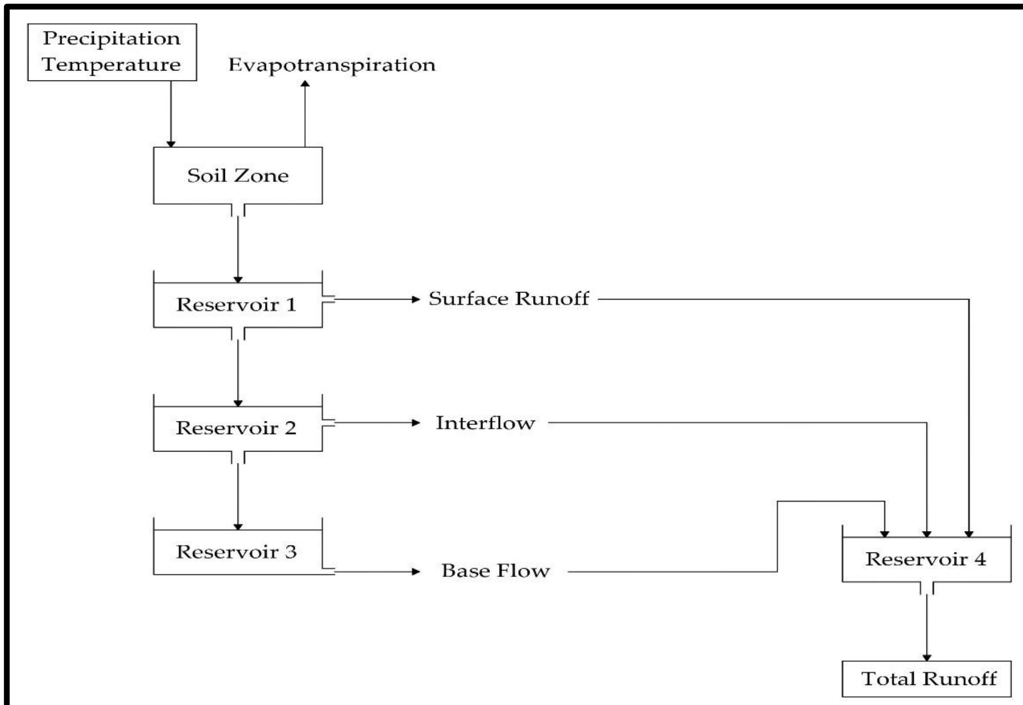

Figure 3. Schematic representation of the conceptual structure of the ENNS model (Nachtnebel et al. 1993).

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Calibration Period Selection (I)

- The period for model calibration was chosen in order to minimize incompatibilities between the mean areal precipitation and the observed discharge.
- The aforementioned incompatibilities were inspected at an annual timescale by using the water balance equation :

$$P - ET_{\mathrm{act}} - RO = 0$$

  where P, ET_{act} and RO are the annual values of precipitation, actual evapotranspiration and measured runoff, respectively.
- This equation is based on the assumption that the change in water storage in the catchment for an annual time step is negligible. Such hypothesis can be supported when the runoff measured at the beginning and end of the hydrologic year does not differ significantly.
- Actual evapotranspiration at an annual level is estimated by using Turc's empirical formula (Turc, 1955).
- Because of the fact that annual runoff values are on average greater than those of annual precipitation, it is expected that most of the years of the investigation period will not satisfy the water balance equation.

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Calibration Period Selection (II)

- Specifically, there is only one hydrological year (1984/85) among all the years on record, that satisfies the water balance equation.
- Figure 4 depicts a period of five consecutive years, from 1984/85 to 1988/89, that incompatibilities between rainfall and measured runoff are expected to be lower. Therefore, it is this period that is selected as **calibration period**.

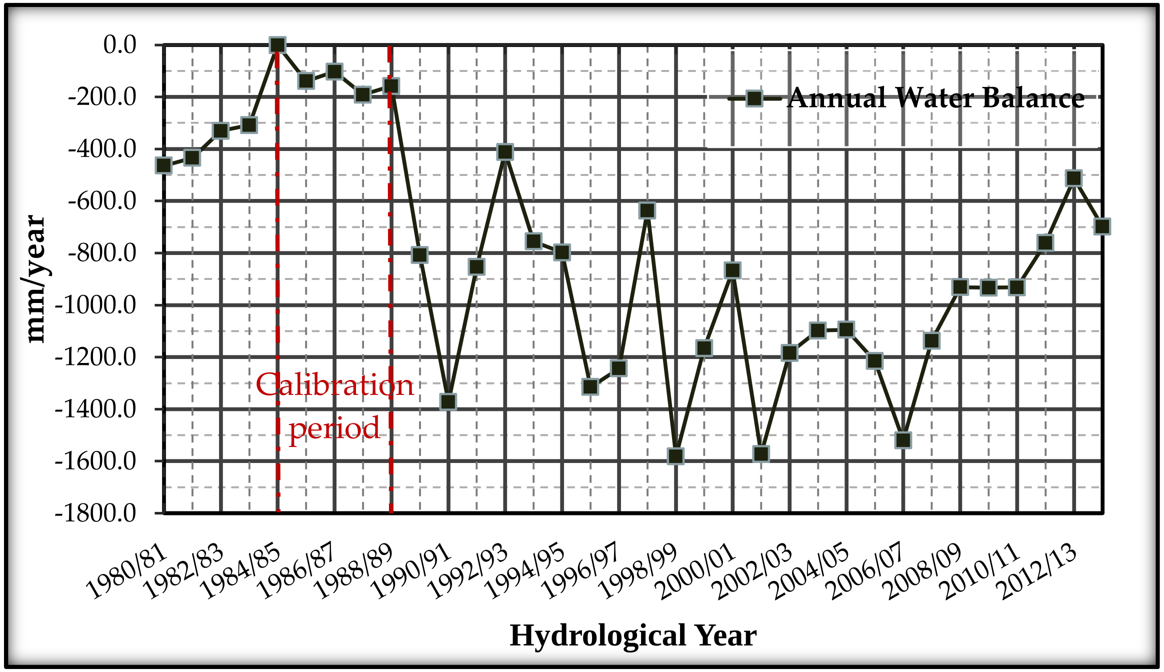

Figure 4. Annual water balance values for the period from 1980/81 to 2013/14 and calibration period

Calibration Criteria and Methodology (I)

- The performance measures used in this study to evaluate the ENNS model simulations during calibration were four widely used criteria (e.g. Chiew *et al.*, 1993; Oudin *et al.*, 2006; Morias *et al.*, 2007) :

$$\mathrm{CrWB} = \frac{\sum_{\mathrm{i}=1}^{n}\left(Q_{\mathrm{obs,i}} - Q_{\mathrm{sim,i}}\right)}{\sum_{\mathrm{i}=1}^{n} Q_{\mathrm{obs,i}}}$$

$$\mathrm{CrQ} = 1 - \frac{\sum_{\mathrm{i}=1}^{n}\left(Q_{\mathrm{obs,i}} - Q_{\mathrm{sim,i}}\right)^2}{\sum_{\mathrm{i}=1}^{n}\left(Q_{\mathrm{obs,i}} - \overline{Q_{\mathrm{obs}}}\right)^2}$$

$$\mathrm{Cr}\sqrt{\mathrm{Q}} = 1 - \frac{\sum_{\mathrm{i}=1}^{n}\left(\sqrt{Q_{\mathrm{obs,i}}} - \sqrt{Q_{\mathrm{sim,i}}}\right)^2}{\sum_{\mathrm{i}=1}^{n}\left(\sqrt{Q_{\mathrm{obs,i}}} - \overline{\sqrt{Q_{\mathrm{obs}}}}\right)^2}$$

$$\mathrm{CrlogQ} = 1 - \frac{\sum_{\mathrm{i}=1}^{n}\left(\log Q_{\mathrm{obs,i}} - \log Q_{\mathrm{sim,i}}\right)^2}{\sum_{\mathrm{i}=1}^{n}\left(\log Q_{\mathrm{obs,i}} - \overline{\log Q_{\mathrm{obs}}}\right)^2}$$

where $Q_{\mathrm{obs,i}}$ and $Q_{\mathrm{sim,i}}$ are the observed and simulated daily runoffs, respectively, while overbars indicate annual mean, and n is the number of days in a hydrological year.

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Calibration Criteria and Methodology (II)

- CrWB expresses the overall water balance error (i.e. model bias) of every simulation at an annual level.
- For the assessment of the model at a daily time scale were used the last three mentioned criteria :
  - CrQ expresses the Nash - Sutcliffe criterion (Nash and Sutcliffe, 1970), and is more sensitive for high runoff values (Oudin *et al.*, 2006), while
  - CrlogQ and Cr$\sqrt{Q}$ consist variants of the Nash – Sutcliffe criterion (Oudin *et al.*, 2006). CrlogQ focuses on low and mid-range flows by transforming stream flow data to logarithmic quantities, while Cr$\sqrt{Q}$ provides a more general evaluation of the overall fit to measured hydrographs.
- All criteria were calculated independently for each annual simulation of the calibration period, in order to ensure that the efficiency of model simulations in worse performing years is not averaged out (see Kaleris and Langousis, 2012).
- The ranges of variation for the most influential parameters of the ENNS model were acquired from previous applications of ENNS to other catchments (see Nachtnebel *et al.*, 1993; Mehleri, 2008; Kaleris and Langousis, 2016). Based on those ranges and while aiming to achieve as high efficiency for the simulations as possible, an **optimal set for the model parameters** resulted.

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Calibration Results and Assessment (I)

- The following figure illustrates the modeled hydrographs, as they resulted for the best preforming parameter set found, in comparison with the measured ones, for all years in the selected calibration period.
- After visual inspection, it can be said that the ENNS model demonstrates a **sufficient skill** in modelling the measured runoff for the calibration period.

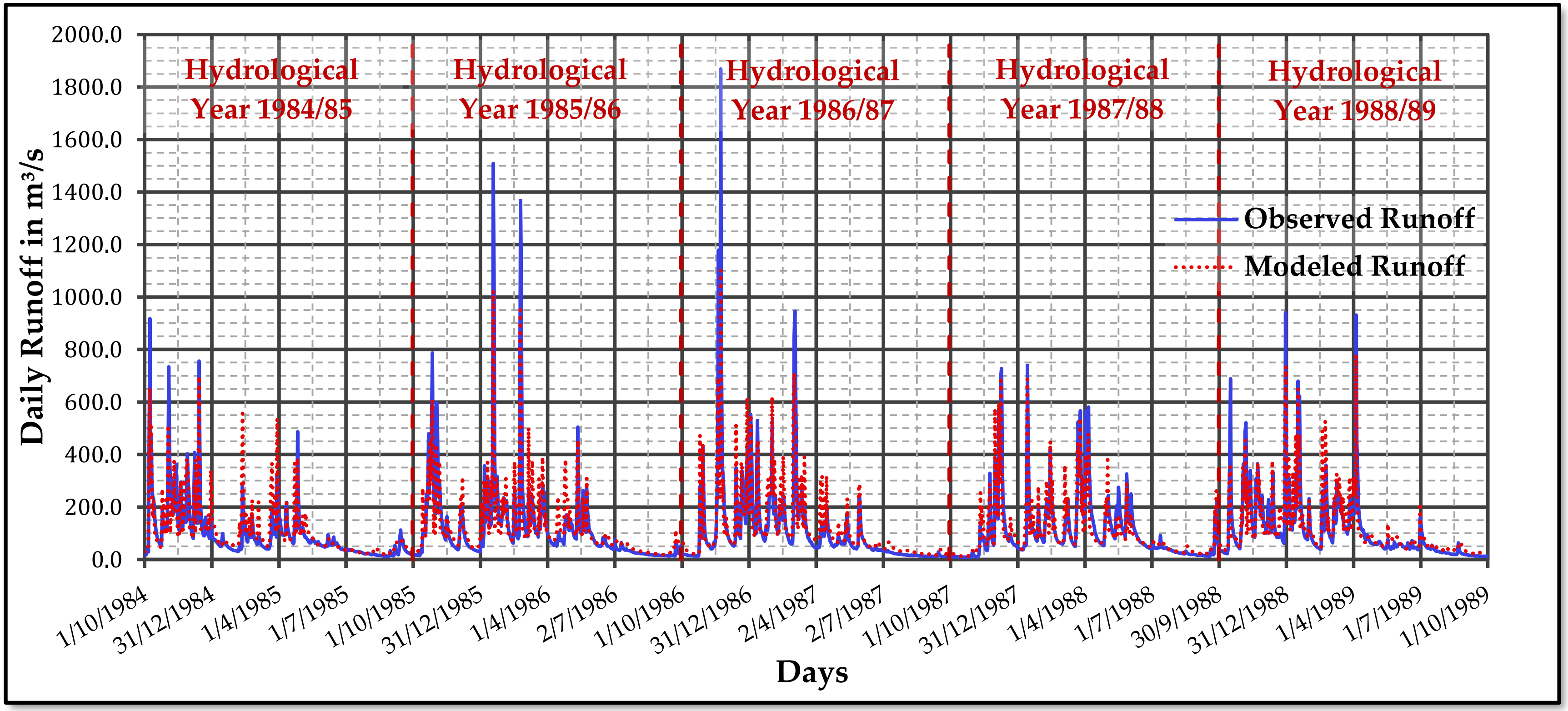

Figure 5. Comparison of measured and simulated hydrographs using the ENNS model for the calibration period

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Calibration Results and Assessment (II)

- More specifically, according to the following figures, Criteria CrQ, Cr$\sqrt{Q}$ and CrlogQ values are large enough to corroborate an **acceptable calibration**.

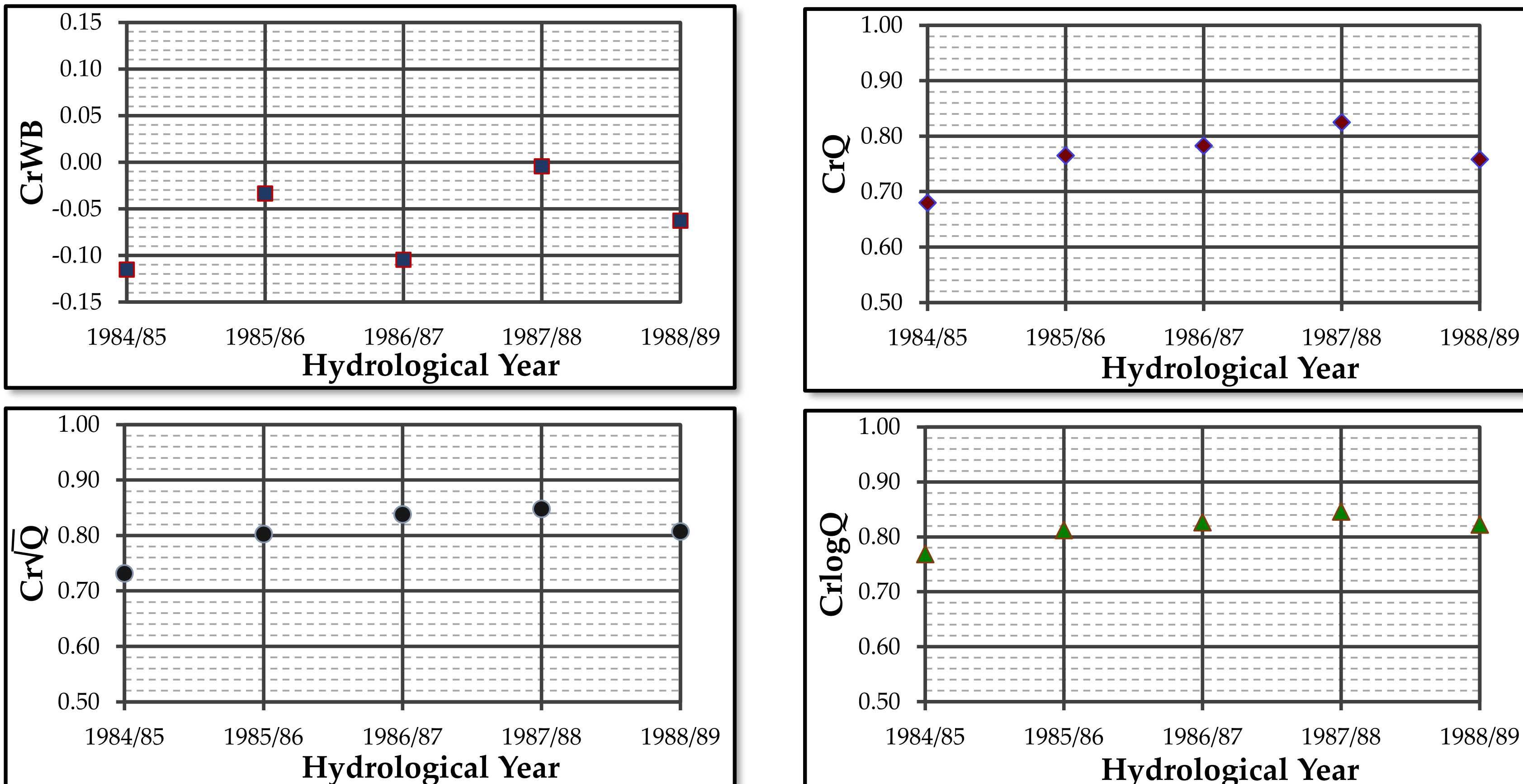

Figure 6. Values of criteria CrWB, CrQ, Cr$\sqrt{Q}$ and CrlogQ for all years in the calibration period

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Model Validation

- The next five years following calibration period were chosen for **model validation**.
- Although model bias values appear slightly greater than those of the calibration period, criteria CrQ, Cr$\sqrt{Q}$ and CrlogQ for the validation period show a similar **good performance** with those of the calibration period.

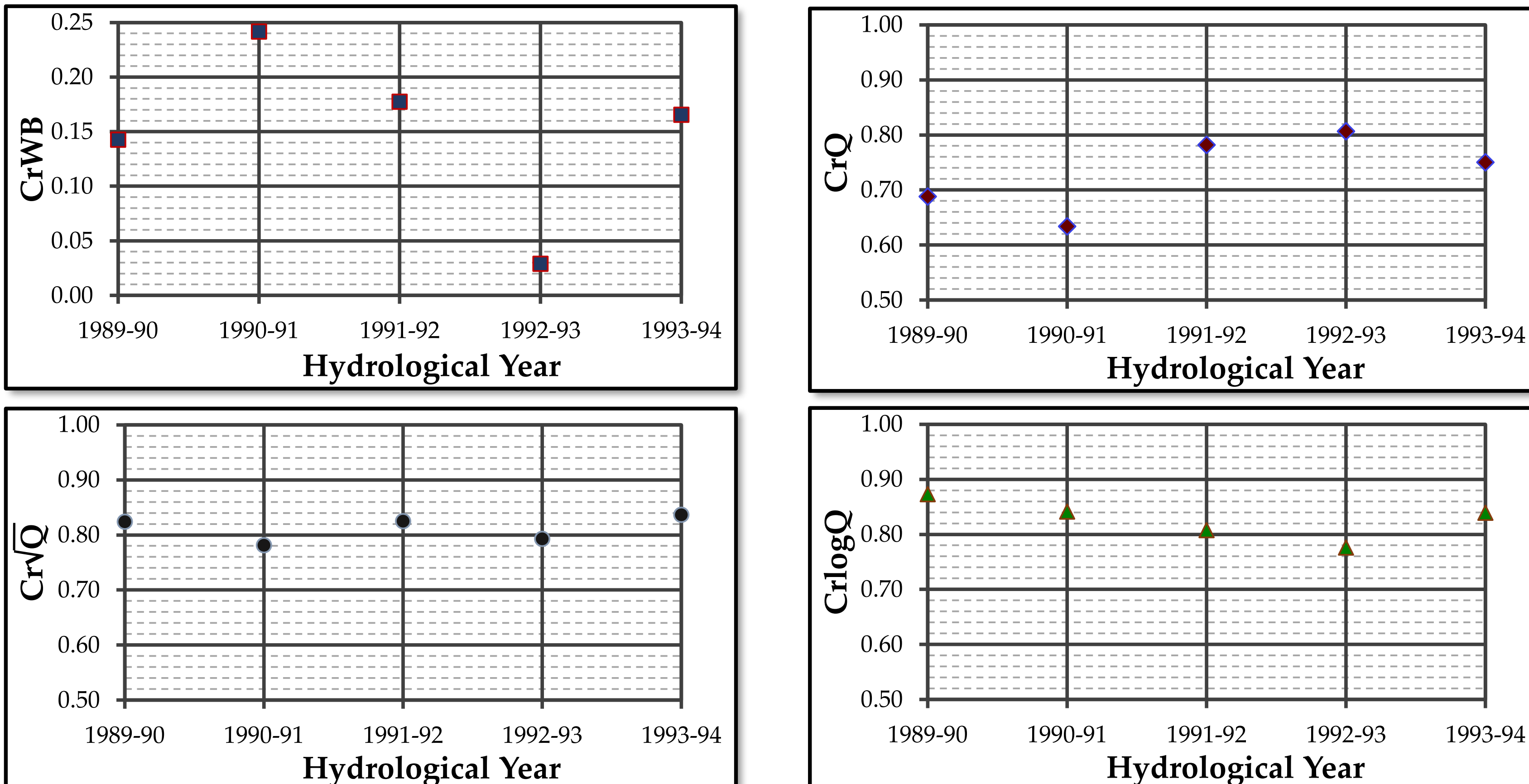

Figure 7. Values of criteria CrWB, CrQ, Cr$\sqrt{Q}$ and CrlogQ for all years in the validation period

Simulation of all Runoff Data (I)

- The ENNS model is considered calibrated to this point. Therefore, it is attempted to simulate all available data of measured discharge (i.e. from 1980/81 to 2013/14).
- Figure 8 shows performance results for all years on record. One can notice that overall the model is able to simulate adequately the measured runoff for the given period, as depicted by the values of $Cr\sqrt{Q}$. In addition, only a small number of points corresponds to a CrQ value below 0.60.
- However, in terms of model bias, its values start increasing significantly after the first decade of the available data. This can be probably attributed to the previously mentioned incompatibilities between basin-averaged rainfall and measured discharge.

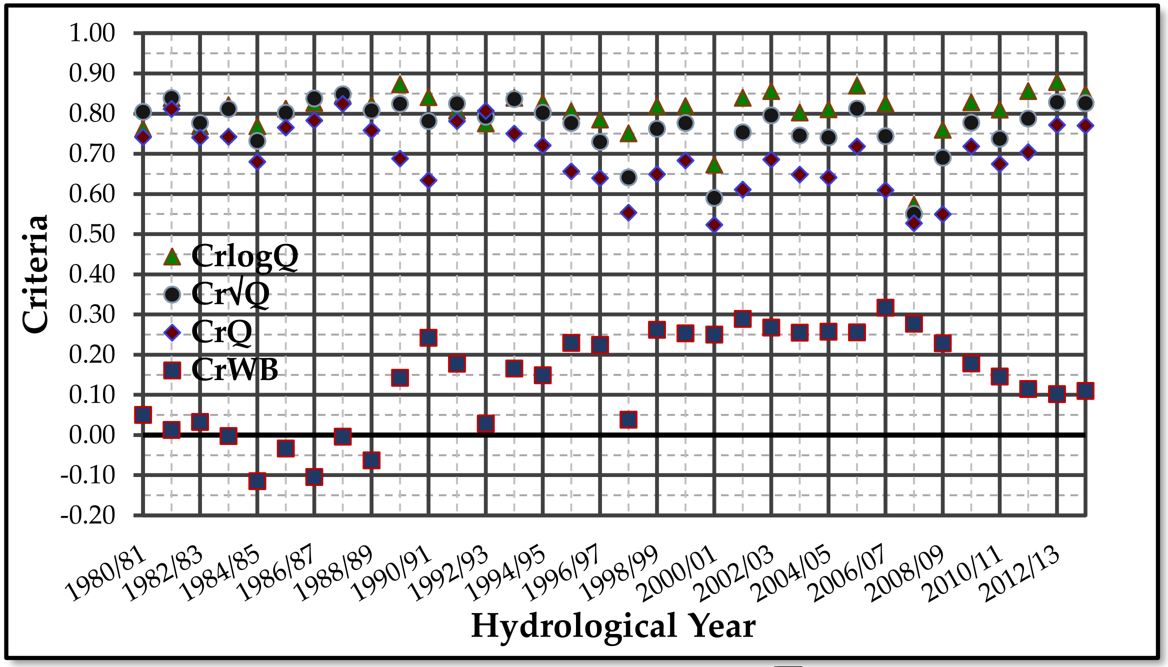

Figure 8. Values of criteria CrWB, CrQ, $Cr\sqrt{Q}$ and CrlogQ for all years on record

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Simulation of all Runoff Data (II)

- Whilst modelling river runoff, the worst performance appeared for hydrological years 1997/98, 2000/01 and 2007/08. It is worth mentioning that although criterion CrQ (Nash – Sutcliffe criterion) is low for year 1997/98, the performance in relation to model bias was really good.
- As shown in Figure 9, the hydrological components of modelled discharge and actual evapotranspiration in conjunction with precipitation, satisfy water balance equation sufficiently at an annual level.

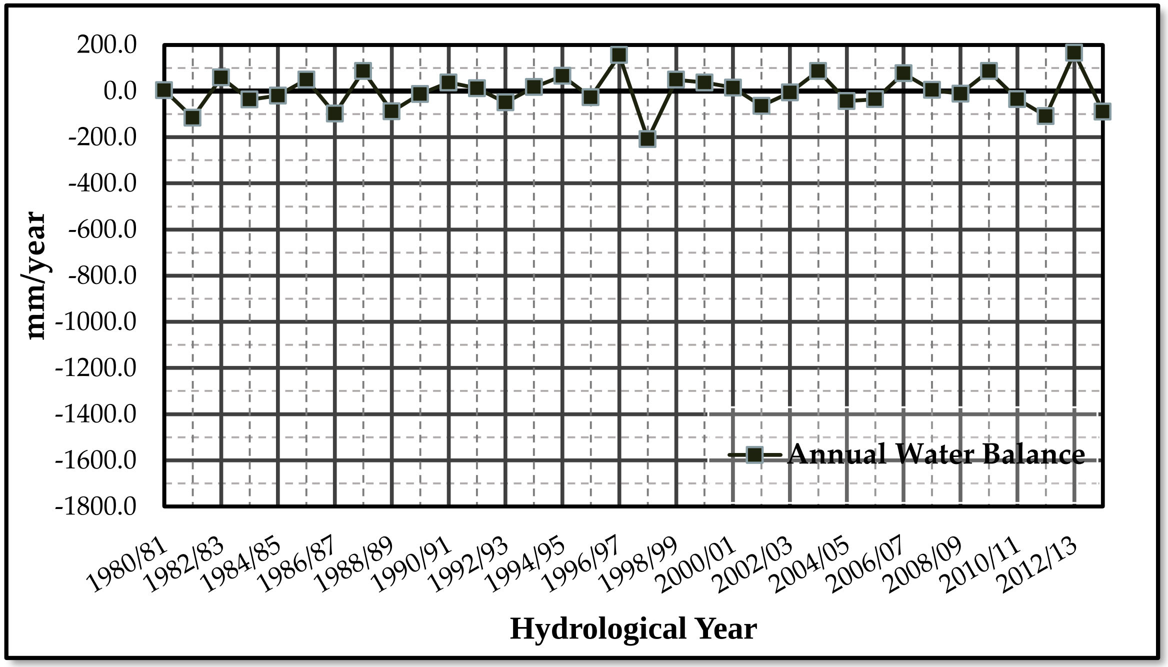

Figure 9. Annual water balance values for all years on record

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Conclusions

- Although the purpose of this work was the conduction of a stochastic analysis between rainfall, measured and model-generated river runoff, the final outcome did not meet our ambitions. The ENNS rainfall-runoff model seemed to be capable of modelling real streamflow data to an extent. Nevertheless, the hydrological modelling is not deemed to be successful, due to simulation results being biased, and thus it cannot be used for the purpose of the aforementioned analysis.
- As cited in section "Precipitation and Runoff Data", the melt of the glaciers in the Olympic Peninsula contributes to runoff of the streams of this area. Were we to know whether the contribution to Queets river runoff is significant and the amount of it, simulation results might be better, though this would require a different modelling approach.
- Since there is not any evidence-based research regarding this specific catchment and the remarkable analogy between precipitation and river runoff, at least not to the authors' knowledge, this topic has a potential for further research.

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