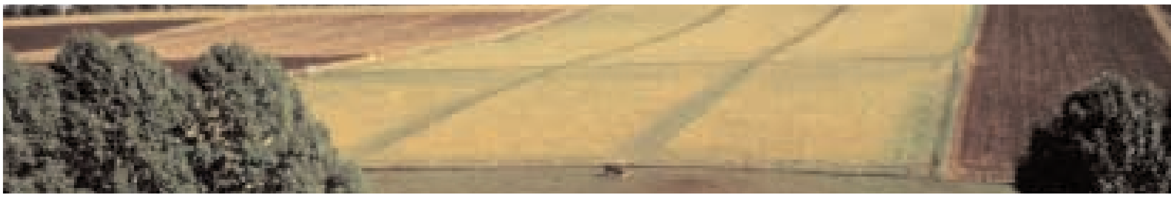
COOPERATIVE RESEARCH CENTRE FOR **CATCHMENT HYDROLOGY**

EVALUATION OF TWO DAILY RAINFALL DATA GENERATION MODELS

TECHNICAL REPORT
Report 02/14
December 2002

Lionel Siriwardena / Ratnasingham Srikanthan / Tom McMahon



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Evaluation of two daily rainfall data generation models

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Evaluation of Two Daily Rainfall Data Generation Models

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Ratnasingham Srikanthan and
Tom McMahon**

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Preface

One of the goals of the Climate Variability Program in the CRC for Catchment Hydrology is to provide water managers and researchers with computer programs to generate stochastic climate data. The stochastic data are needed at time scales from less than one hour to a year and for point sites to large catchments like the Murrumbidgee and Fitzroy.

The first technical report in this series, 'Stochastic Generation of Climate Data: A Review' (CRC Technical Report 00/16), reviewed methods of stochastic generation of climate data and recommended the testing of a number of techniques. The second technical report, 'Stochastic Generation of Annual Rainfall Data' (CRC Technical Report 02/6), compared the first order autoregressive and hidden state Markov models for the generation of annual rainfall data. The third technical report, 'Stochastic Generation of Monthly Rainfall Data' (CRC Technical Report 02/8), evaluated the method of fragments and a nonparametric model for the generation of monthly rainfall data.

This report evaluates the Transition Probability Matrix model with Boughton's correction for interannual variability (TPM) and the simplified Daily and Monthly Mixed (DMMS) model for the generation of daily rainfall data. The report also compares the statistical characteristics of the daily, monthly and annual streamflow data simulated by a rainfall-runoff model using stochastic daily rainfall obtained using the TPM and DMMS models with the historical streamflow characteristics.

Dr Francis Chiew
Program Leader
Climate Variability Program

Summary

The work reported here covers part of the Project 5.2 of CRC for Catchment Hydrology - "National Data Bank of Stochastic Climate and Streamflow Models". The project aims to develop a robust set of stochastic models for generation of rainfall, streamflow and other climatic data. This report is focused on the generation of daily rainfall data and synthesising long daily streamflow sequences by transforming generated rainfall through a simple rainfall-runoff model.

The study concentrated on evaluating the performance of two daily rainfall data generation models, Transition Probability Matrix (TPM) model with Boughton's correction and a simplified Daily and Monthly Mixed (DMMS) model, by applying them to eight catchments located in Australia. The models were assessed on their ability to preserve daily, monthly and annual characteristics of historical rainfall. As an important process of evaluation, generated rainfall sequences were transformed to daily streamflow sequences using a calibrated rainfall-runoff model (SIMHYD). The models were then assessed in relation to their ability to preserve appropriate streamflow characteristics of the modelled streamflow from historical rainfall.

It was shown that both models preserved key statistical characteristics of historical rainfall satisfactorily at daily, monthly and annual levels. However, the DMMS model poorly simulates the rainfall amounts on different types of wet days (solitary wet days, wet days bounded on one side by a wet day and wet days bounded on both sides by wet days) whereas the TPM model preserves these characteristics adequately. The major drawback of the TPM model over the DMMS model is its inability to preserve correlation between monthly rainfalls; the DMMS model preserves this statistic satisfactorily.

There is no clear distinction between the two rainfall generation models in their overall performance with respect to preserving characteristics of daily, monthly and annual streamflow when the models are used as input to the SIMHYD rainfall-runoff model. Both rainfall generation models perform satisfactorily within their scope in the overall modelling approach. However, the event modelling for synthesised streamflow indicated that the TPM model is more consistent in preserving various characteristics of event flow volumes and peak flow rates.

Overall, the TPM model is the slightly better model with a greater consistency in preserving different daily, monthly and annual characteristics of historical rainfall and having ability to model catchments of different characteristics with the same degree of success. However, it requires a large number of parameters to be estimated.

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1. Introduction

The work reported here covers part of the Project 5.2 of CRC for Catchment Hydrology - "National Data Bank of Stochastic Climate and Streamflow Models". The project aims to develop a robust set of stochastic models for generation of rainfall, streamflow and other climatic data. This report is focused on the generation of daily rainfall data and synthesising long daily streamflow sequences by transforming generated rainfall through a simple rainfall-runoff model.

The need to assess and quantify the uncertainty in hydrologic systems due to climatic variability has been drawn to the attention of researchers and industry in recent times. This need applies whether the systems are complex water resources systems or simple planning models of catchment behaviour. For the majority of systems, the risk assessment involves system simulation using stochastically generated rainfall, streamflow and other climate data. In addition to quantifying the uncertainty, stochastically generated data have many applications such as the design and operation of water resources systems, design of urban drainage systems and evaluating the impact of land use changes.

Streamflow records are the primary basis for planning and designing a water resources system. An important application of daily rainfall generation is to synthesise long streamflow sequences by inputting generated rainfall into a calibrated rainfall-runoff model. Streamflows synthesised from stochastically generated rainfalls allow the assessment of system reliability and risk associated with the system due to climatic variability.

Stochastic models of daily rainfall can generally be divided into two parts, a model of rainfall occurrence, which provides a sequence of dry and wet days, and a model of rainfall amounts, which simulates the amount of rainfall occurring on each wet day. Models of rainfall occurrence are commonly based on Markov chains. These models specify the state of each day as 'wet' or 'dry' and develop a relation between the state of the current day and the states of preceding days. Models used for rainfall amounts include the two-parameter Gamma distribution, the Exponential distribution and the skewed Normal distribution. A comprehensive review of approaches used to generate daily rainfalls is given in Srikanthan and McMahon (1985, 2000).

Srikanthan and McMahon (1985) adopted a multi-state Transition Probability Matrix (TPM) approach to develop a daily rainfall data generation model. The daily rainfalls are grouped into classes of given magnitude ranges with the lowest class being the dry state. The probabilities are calculated for transition from each class to any other. The rainfall values in the last class are modelled by a Box-Cox transformation and the values in the intermediate classes are modelled by a linear distribution. In a subsequent modification, shifted Gamma distribution is used to model the last class.

In most daily generation models, monthly and annual characteristics are not preserved adequately. Boughton (1999) observed that the TPM model underestimates the standard deviation of annual rainfall and proposed an empirical adjustment to match the observed standard deviation.

Wang and Nathan (2002) developed a daily and monthly mixed (DMM) algorithm for the generation of daily rainfall. Daily rainfall data are generated month by month using the traditional two part model using two sets of parameters for the Gamma distribution; one estimated from the daily rainfall data and the other from monthly rainfall data. The generated monthly rainfalls are modified to preserve the monthly serial correlation and the modified monthly values are used to adjust the generated daily rainfall values. The model preserves the daily and monthly characteristics but underestimates the standard deviation of the annual rainfall in some cases.

Chapman (1994) highlighted the importance of preserving the different statistics for rainfall amounts on wet days bounded by different number of adjoining wet days, eg. solitary wet days, one and both sides bounded wet days. Preservation of these characteristics is considered important for daily runoff generation. Zhou *et al.* (2002), assessing the performance of four daily rainfall generation models, found that the Daily and Monthly Mixed (DMM) model did not preserve the mean rainfall on these types of wet days, whereas the Transition Probability Matrix (TPM) model preserves the characteristics adequately. They also found that a modified TPM model, with a correction for standard deviation (Boughton, 1999), adequately models daily rainfalls at all 21 sites tested.

The Daily and Monthly Mixed (DMM) model (Wang and Nathan, 2002) can be simplified by generating only one daily sequence and adjusting it to preserve the monthly mean, standard deviation and serial correlation coefficient. This simplified model (DMMS) is used in this study.

Successful development of a generation model requires adequate testing with regard to characteristics at different time scales and at a number of locations in different climates. For instance, a daily generation model should preserve the observed monthly and annual characteristics in addition to preserving various daily characteristics.

The aim of this study is to evaluate and compare the performance of the two daily rainfall generation models noted above, namely the Transition Probability Matrix (TPM) model with Boughton's adjustment and the simplified Daily and Monthly Mixed (DMMS) model. The models are evaluated by applying them to eight catchments located in Australia. The models are assessed on their ability to preserve daily, monthly and annual characteristics of historical rainfall data by comparing various statistics. As an important process of evaluation, generated rainfall sequences are transformed to daily streamflow sequences using a calibrated rainfall-runoff model (SIMHYD), and the resulting synthetic streamflows are assessed in relation to their ability to preserve appropriate daily, monthly and annual characteristics of historical streamflow data. This allows the selection of the better rainfall generation model for obtaining generated streamflow as the end product.

The report begins with a description of the catchments and data used in the study. The TPM and DMMS rainfall generation models, are described in Chapter 3. The structure of the rainfall-runoff model, SIMHYD, and the calibrated parameters for the selected catchments are described in Chapter 4. The performance of the TPM and DMMS models with respect to generation of rainfall and streamflow is evaluated in Chapters 5 and 6 respectively. Chapter 7 contains a discussion of the results, with conclusions drawn from the study presented in Chapter 8.

2. Selection of Catchments

This study is concerned with the testing of two daily rainfall generation models at a catchment scale using long records of areally averaged daily rainfall data. As part of the model evaluation process, synthesised streamflow sequences need to be derived from historical and generated rainfall, in conjunction with a suitable rainfall-runoff model calibrated for the catchment.

It is not the intention of this work to carry out a comprehensive study on rainfall-runoff modelling. Hence, the selection of suitable catchments is based on previous studies. Chiew *et al.* (2002) applied and tested a simple conceptual daily rainfall-runoff model SIMHYD on over 300 catchments across Australia with a wide range of climatic and physical characteristics. SIMHYD has seven parameters and estimates streamflow from daily rainfall and areal potential evapotranspiration data. The results indicate that SIMHYD can estimate streamflow satisfactorily for practically all the catchments (Chiew *et al,* 2002). The description of the model and the calibrated parameters for selected catchments are given in Chapter 4.

The criteria for selection of catchments were primarily based on the following points:

- catchments should be small to medium sized (50 - 800 km^2);
- catchments should be selected from across Australia and be representative of various climatic regimes;
- there should be good streamflow data at the catchment outlet (gauging station at the catchment outlet);
- there should be long records of daily rainfall data and
- the calibration results of the rainfall-runoff model applied to the catchments should be satisfactory.

Eight catchments were selected from the 300 available that satisfy the above criteria, particularly, having excellent SIMHYD rainfall-runoff model calibration results based on the work carried out by Chiew *et al.* (2002). Calibration and validation of the SIMHYD modelling satisfy the following performance statistics for the eight catchments:

- coefficient of efficiency of monthly flows for the *calibration period* is greater than 0.90;
- coefficient of efficiency of monthly flows for the *validation period* is greater than 0.85;
- ratio of modelled to historical streamflow volume for the *calibration period* is within 0.95-1.05;
- ratio of modelled to historical streamflow volume for the *validation period* is within 0.95-1.05;
- ratio of modelled to historical coefficient of variation for annual flows (Cv) for the *calibration period* is within 0.95-1.05;
- ratio of modelled to historical coefficient of variation for annual flows (Cv) for the *validation period* is within 0.95-1.08 and
- ratio of modelled to historical baseflow volume is within 0.90-1.10.

The calibration of rainfall-runoff model for these catchments was based on at least 25 years of continuous streamflow data.

The selected catchments are listed in Table 2.1 and shown in Figure 2.1.

Long records of historical daily rainfall are required as input to the rainfall generation models and calibrated rainfall-runoff model. Continuous rainfall data over a period of 110 years from 1889 to 1998 were used in this study. The source of the daily rainfall data is the Queensland Department of Natural Resources 0.05° x 0.05° (about 5 km x 5 km) interpolated gridded rainfall data based on over 6000 rainfall stations in Australia (see www.dnr.qld.gov.au/silo). The interpolation uses ordinary krigging of monthly rainfall data, and a variogram with zero nugget and a variable range. The monthly rainfall for each 5 km x 5 km point is then disaggregated to daily rainfall using the rainfall distribution from the closest rainfall station to the point. The lumped catchment averaged daily rainfall used here is estimated from the daily rainfall in 5 km x 5 km points within each catchment.

Figure 2.2 shows the monthly rainfall distribution of the selected catchments. The mean annual rainfall varies from 710 to 2170 mm. Three of the catchments (in Qld and NSW) have dominant rainfall during summer months and the rest have dominant rainfall during winter months.

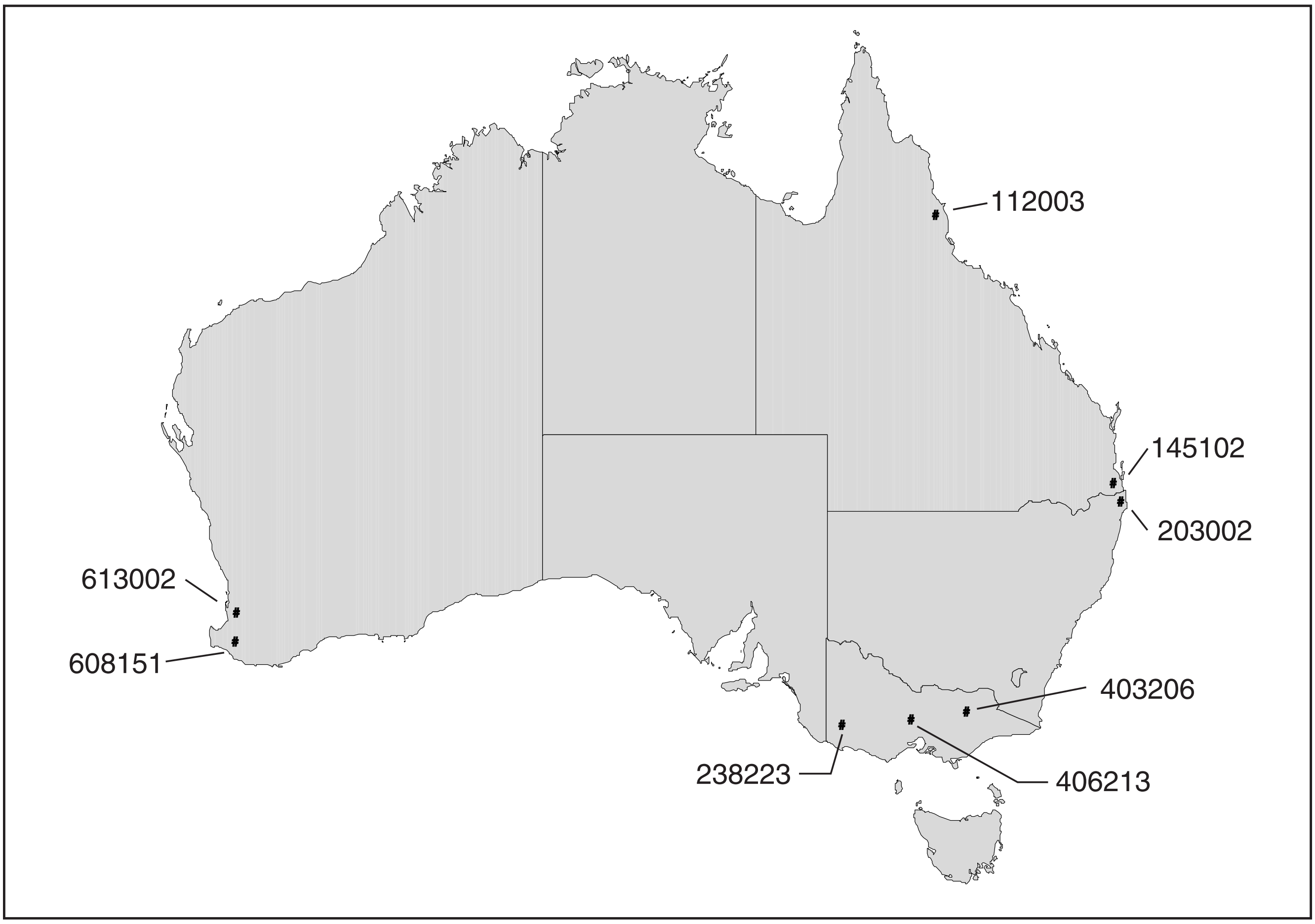


Figure 2.1 Locations of catchments used for the study

Table 2.1 Details of catchments selected for the study

State	Station Number	Station Name	Long °E	Lat °S	Area km²	Annual rainfall (mm)	Rainfall period	Stream-flow period
QLD	112003	North Johnstone R.@ Glen Allen	145.59	17.36	169	1908	1889-1998	1959-97
QLD	145102	Albert River @ Bromfleet	153.05	27.92	547	1318	1889-1998	1919-98
NSW	203002	Coopers Creek @ Repentance	153.39	28.64	61	2071	1889-1998	1976-98
VIC	238223	Wando River @ Wando Vale	141.62	37.50	177	710	1889-1998	1965-96
VIC	403206	Buckland River @ Buckland	146.88	36.90	323	1411	1889-1998	1945-73
VIC	406213	Campaspe River @ Redesdale	144.53	37.20	638	770	1889-1998	1959-96
WA	608151	Donnelly River @ Strickland	116.02	34.15	784	1063	1889-1998	1955-98
WA	613002	Harvey River @ Dingo Rd	116.08	32.99	151	1159	1889-1998	1970-98

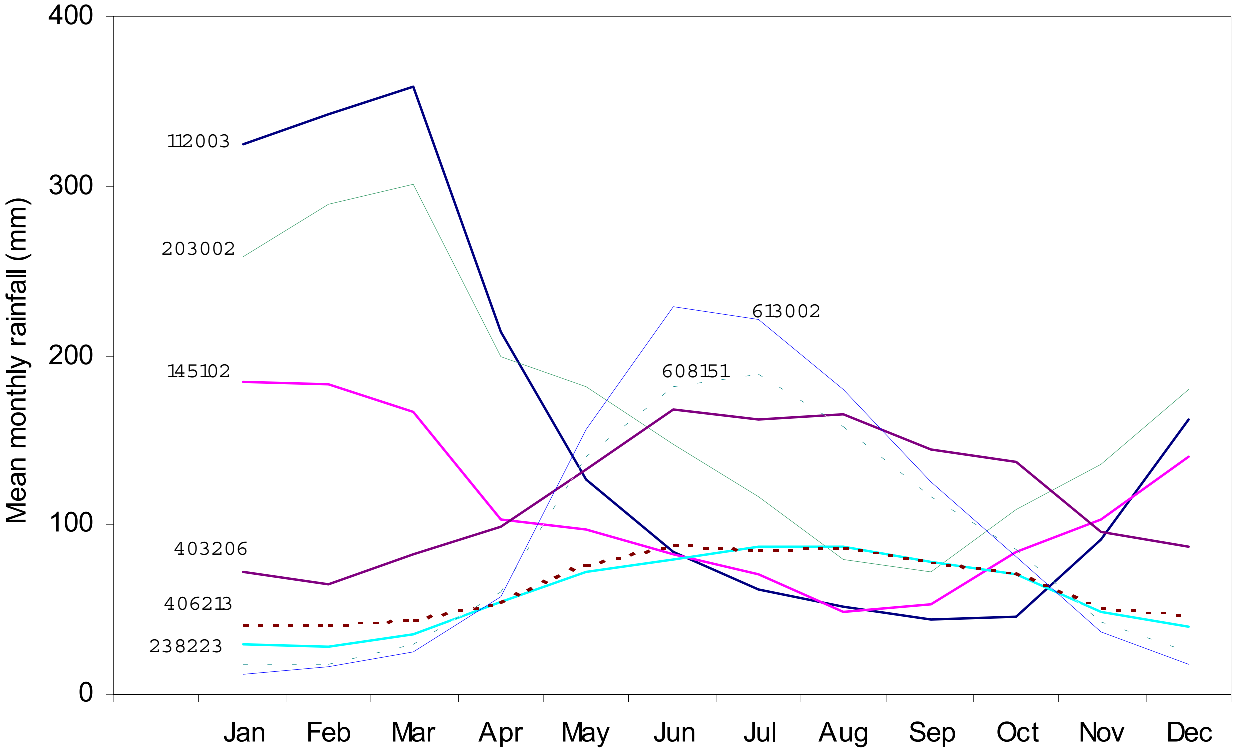


Figure 2.2 Monthly rainfall distribution of selected catchments

3. Description of Rainfall Data Generation Models

This study uses two daily rainfall generation models, namely, the Transition Probability Matrix (TPM) model and a simplified Daily and Monthly Mixed (DMMS) model to generate synthetic sequences of daily rainfalls for the study catchments. The models can be used to generate a large number of replicates that are equally likely to occur; the performance of the two models can then be evaluated by comparing various statistical properties of the generated sequences with the properties of the historical sequence.

3.1 Transition Probability Matrix (TPM) Model

The model used in this study is a variation of the algorithm developed by Srikanthan and McMahon (1985). The rainfall amount of the last state is modelled by a shifted Gamma distribution instead of the Box-Cox transformation used in the original model. An empirical adjustment factor (Boughton, 1999) is incorporated to preserve the standard deviation of the annual rainfall.

In the Transition Probability Matrix (TPM) model, the seasonality in occurrence and magnitude of daily rainfall is taken into account by considering each month separately. The daily rainfall are divided into a number of states, up to a maximum of seven. State 1 is dry (no rainfall) and the other states are wet. The number of states for each month can be determined from the guidance given in Srikanthan and McMahon (1985). The state boundaries for rainfall amounts are given in Table 3.1. If the number of states is less than seven the upper limit of the last state is infinite.

The shifted Gamma distribution is used to model rainfall amounts for the last state, while a linear distribution is used for the intermediate states. The latter is chosen because daily rainfall usually exhibits a J shape distribution.

Table 3.1 State boundaries for rainfall amounts in the TPM model (after Srikanthan and McMahon, 1985)

State number	Upper state boundary limit (mm)
1	0.0
2	0.9
3	2.9
4	6.9
5	14.9
6	30.9
7	∝

The transition probabilities are estimated from

$$p_{ij}(k) = \frac{f_{ij}(k)}{\sum_{j=1}^{C} f_{ij}(k)} \qquad (3.1)$$

$$i, j = 1, 2, \ldots, C; \; k = 1, 2, \ldots, 12$$

where $f_{ij}(k)$ = historical frequency of transition from state i to state j within month k, and

C = the maximum number of states.

The Gamma distribution parameters are obtained by the method of moments.

The daily rainfall data are generated by following the steps set out below, assuming that the initial state is dry (that is, state one).

Step 1: Generate a uniformly distributed random number between 0 and 1. Using the appropriate TPM for the month, determine the state of the next day.

Step 2: If the state is wet, go to step 3. Otherwise, set the rainfall depth to zero and go to step 1.

Step 3: Calculate the rainfall depth by using the linear distribution for the intermediate states and shifted Gamma distribution for the largest state.

Step 4: Repeat steps 1 to 3 until the required length of daily rainfall data is generated.

The model can be improved by adopting an empirical adjustment factor (F) to match the observed standard deviation of the annual rainfall (Boughton, 1999). The adjustment factor is obtained by trial and error until the frequency distribution of the observed and generated annual rainfalls matches. The generated daily rainfall in each year is multiplied by the following ratio:

$$Ratio_i = \frac{\{M + (T_i - M)F\}}{T_i} \qquad (3.2)$$

where M = the observed mean annual rainfall,
and

T_i = the generated annual rainfall for year i.

Since the slope of the frequency curve is proportional to the standard deviation, the adjustment factor can be directly obtained as a ratio of the standard deviation of the generated and observed annual rainfall. Thus:

$$F = \frac{stdev_g}{stdev_o} \qquad (3.3)$$

The adjusted annual total is obtained from

$$T_i' = G + (T_i - G)F \qquad (3.4)$$

where G is the generated mean annual rainfall.

By dividing both sides of Eq (3.4) by T_i, we obtain the ratio of the adjusted annual rainfall to the unadjusted generated annual rainfall.

$$\frac{T_i'}{T_i} = \frac{\{G + (T_i - G)F\}}{T_i} \qquad (3.5)$$

Eq (3.5) is identical to Eq (3.2) except that the observed mean (M) in Eq (3.2) is replaced by G in Eq (3.5). This minimises the bias in the mean rainfall.

The standard deviation of the generated annual rainfall is estimated from a number of replicates and averaged. The ratio of this adjusted value to the observed value is taken as F for adjusting the daily values.

3.2 Simplified Daily and Monthly Mixed (DMMS) Model

In this model, the occurrence of rainfall is determined by using a first order Markov chain using the two transition probabilities: $P_{W|D}$, the conditional probability of a wet day given that the previous day was dry; $P_{W|W}$, the conditional probability of a wet day given that the previous day was wet. The unconditional probability of a wet day can be derived as

$$\pi = \frac{p_{W|D}}{1 + p_{W|D} - p_{W|W}} \tag{3.6}$$

The rainfall depth is obtained from a Gamma distribution whose probability density function is given by

$$f(x) = \frac{(x/\beta)^{\alpha-1}\exp(-x/\beta)}{\beta\Gamma(\alpha)} \tag{3.7}$$

where α is the shape parameter and β the scale parameter. The mean and variance of the Gamma distribution are given by

$$\mu(x) = \alpha\beta \tag{3.8}$$

$$\sigma^2(x) = \alpha\beta^2 \tag{3.9}$$

The mean and variance of the rainfall total, X, over a month of N days is given by (Katz, 1983, 1985)

$$\mu(X) = N\pi\alpha\beta \tag{3.10}$$

$$\sigma^2(X) = N\pi\alpha\beta^2\left[1 + \alpha(1-\pi)\frac{1 + p_{W|W} - p_{W|D}}{1 - p_{W|W} + p_{W|D}}\right] \tag{3.11}$$

The simplified Daily and Monthly Mixed (DMMS) model involves the following steps.

Step 1: For month i, generate a sequence of wet and dry days for the whole month using a two-state first order Markov chain.

Step 2: For any wet day in that month, generate a daily rainfall amount x^d from a Gamma distribution with parameters $\alpha = \alpha^d$ *and* $\beta = \beta^d$ which are estimated from the mean and variance of daily rainfall amounts by using Eq (3.8) and (3.9).

Step 3: Manipulate the monthly total of the daily rainfall generated in step 2, $\widetilde{X}_i = \sum x^d$, to produce a new monthly total X_i by using the Thomas-Fiering monthly model.

$$\frac{X_i - \mu(X_i)}{\sigma(X_i)} = \rho_{i,i-1}\frac{X_{i-1} - \mu(X_{i-1})}{\sigma(X_{i-1})} + (1-\rho_{i,i-1}{}^2)^{1/2}\frac{\widetilde{X}_i - \mu'(X_i)}{\sigma'(X_i)} \tag{3.12}$$

where $\rho_{i,i-1}$ is the correlation coefficient between months i and i-1, and the subscripts i-1 and i in Eq (3.12) denote the previous and current months respectively.

The mean $\mu'(X_i)$ and standard deviation $\sigma'(X_i)$ used in Eq (3.12) are obtained from Eq (3.10) and (3.11) using the daily Gamma parameters obtained in step 2.

Step 4: Produce a new daily rainfall series x for that month by multiplying all the x^d by a factor $(X_i / \sum x^d)$.

The DMMS generates only one sequence of daily rainfall amounts, but at the same time adjusts the daily rainfall to match the monthly characteristics. On the other hand, the original model generates two daily rainfall series, the first and second reproducing daily and monthly statistics respectively, and subsequently use the second series (after incorporation of autocorrelation) to adjust the first series. Furthermore, in the original model, lag one autocorrelation is estimated from the non-seasonal data.

4. Description of Rainfall-Runoff Model

As a part of the rainfall generation model evaluation, a calibrated rainfall-runoff model is used to derive synthesised daily streamflow sequences from historical rainfall series and generated rainfall replicates. For this purpose, the simple conceptual daily rainfall-runoff model SIMHYD (Chiew *et al.*, 2002) is used in this study. The model has seven parameters and estimates streamflow from daily rainfall and areal potential evapotranspiration data.

4.1 SIMHYD Rainfall-Runoff Model Structure

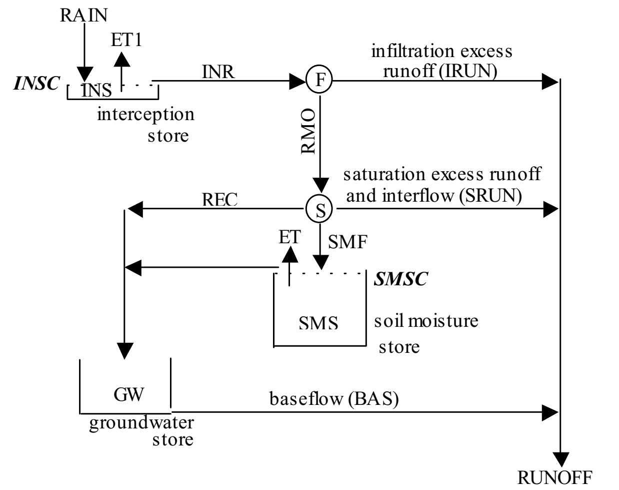
The structure of the SIMHYD model is shown in Figure 4.1, with its seven parameters highlighted in bold italics. A brief description of the processes in SIMHYD is given here. For more detail, refer to Chiew *et al.* (2002).

In SIMHYD, a rainfall event first fills the interception store, which is depleted each day by evaporation subject to potential evapotranspiration rate. The excess rainfall is subjected to an infiltration function. The excess rainfall that exceeds the infiltration capacity becomes infiltration excess runoff.

Moisture that infiltrates is subjected to a soil moisture function that diverts water to the stream (interflow), groundwater store (recharge) and soil moisture store. Interflow is first estimated as a linear function of the soil wetness, defined as the ratio of soil moisture storage to soil moisture capacity. This linear function attempts to mimic the saturation excess runoff processes with the soil wetness used to reflect parts of the catchment that are saturated from which saturation excess runoff (interflow) can occur. Groundwater recharge is then estimated, also as a linear function of the soil wetness. The remaining moisture flows into the soil moisture store.

Evapotranspiration from the soil moisture store is estimated as a linear function of the soil wetness, subject to the evapotranspiration from the interception store and the soil moisture store together not exceeding the atmospherically controlled rate of areal potential evapotranspiration. The water that exceeds the capacity of the soil moisture store overflows into the groundwater store. Baseflow from the groundwater store is simulated as a linear recession from the store.

The model therefore estimates runoff generation from three sources, ie. infiltration excess runoff, interflow (saturation excess runoff) and baseflow. The routing of streamflow is ignored.



PET = areal potential evapotranspiration (input data)
INR = max{(RAIN + INS - INSC) , 0.0}
ET1 = lesser of (INS, PET)
RMO = lesser of {***COEFF*** exp(-***SQ*** x SMS/***SMSC***), INR}
IRUN = INR - RMO
SRUN = ***SUB*** x SMS/***SMSC*** x RMO
REC = ***CRAK*** x SMS/***SMSC*** x (RMO - SRUN)
SMF = RMO - SRUN - REC
POT = PET - ET1
ET = lesser of {10 x SMS/***SMSC***, POT}
BAS = ***K*** x GW

Model Parameters
INSC interception store capacity (mm)
COEFF maximum infiltration loss (mm)
SQ infiltration loss exponent
SMSC soil moisture store capacity (mm)
SUB constant of proportionality in interflow equation
CRAK constant of proportionality in groundwater recharge eqn.
K baseflow linear recession parameter

Figure 4.1 Structure of the conceptual rainfall-runoff model SIMHYD

4.2 Model Calibration and Validation

The SIMHYD model runs on a daily time step, but is calibrated against monthly streamflows. The seven model parameters are optimised to minimise an objective function which is defined as the sum of squares of the difference between the estimated and recorded monthly streamflows. During the calibration process, penalties are applied if the total estimated and recorded runoff volumes differ significantly and the coefficient of variation of the estimated annual runoff differs significantly from that of the recorded annual runoff. An automatic pattern search optimisation technique is used to calibrate the model, with 10 different parameter sets used as starting points, to increase the likelihood of finding the global optimum parameter values (Chiew *et al.*, 2002).

The cross-validation is carried out to assess whether the optimised parameter values can successfully estimate streamflow for an independent test period that is not used in the model calibration. This is undertaken by dividing the available streamflow data into three almost equal parts. Each part is left out in turn, and SIMHYD is calibrated against streamflow data in the remaining two parts. The optimised parameter values are then used to estimate runoff for the part that was left out, and the estimated flows are compared with the recorded flows.

Some of the objective measures that can be used to assess the model performance are :

- coefficient of efficiency between estimated and recorded monthly streamflow;
- ratio of estimated and recorded streamflow volume;
- ratio of coefficient of variation (CV) of estimated and recorded annual streamflow;
- ratio of baseflow indices (BFI) derived from estimated and recorded streamflow series.

These measures need to be derived for the calibration and validation periods independently. Performance statistics close to 1.0 indicate that the calibrated rainfall-runoff model performs satisfactorily.

4.3 Calibrated Model Parameters for Study Catchments

Calibrated SIMHYD model parameters for the eight selected catchments are given in Table 4.1. The calibration and validation procedure used the entire record of available historical streamflow data. Table 4.2 provides a summary of performance statistics of the calibrated model.

The performance statistics derived in Table 4.2 are on a monthly or an annual basis (except the BFI), and it

Table 4.1 Calibrated SIMHYD model parameters

Station	INSC	COEFF	SQ	SMSC	SUB	CRAK	K
112003	4.71	336	1.875	31.3	0.087	0.975	0.018
145102	5.00	146	1.200	479.4	0.225	0.500	0.158
203002	5.00	399	1.525	165.0	0.300	0.375	0.210
238223	5.00	400	7.050	270.0	0.009	0.550	0.065
403206	2.33	400	3.188	407.5	0.000	0.434	0.065
406213	5.00	360	4.438	175.0	0.000	0.419	0.080
608151	4.90	300	1.000	500.0	0.159	0.450	0.069
613002	5.00	400	2.125	465.0	0.175	0.500	0.025

is evident from the results that the calibrated SIMHYD model performs satisfactorily on monthly basis for all the catchments selected.

The performance of the calibrated SIMHYD rainfall-runoff model on a daily basis was evaluated by comparing daily flow duration curves derived from modelled streamflow using historical daily rainfall against those from recorded daily streamflow. The results are shown in Figure A.1 (Appendix A). These figures show significant differences between the two curves for most of the catchments, which occur because these models are calibrated on monthly streamflow data rather than on daily streamflow data. Furthermore, it should be noted that the modelled streamflow is not subject to routing and hence, the effect of attenuation on the modelled streamflow is ignored. This could lead to a systematic bias on the comparison plots.

Table 4.2 Performance statistics of modelled streamflow for selected catchments

Catcode	Calibration period	CE	Cr1	Cr2	VE	Vr1	Vr2	DBFI (% diff.)
112003	1959-97	0.94	0.95	1.02	0.93	0.96	0.99	-3.03
145102	1919-98	0.91	1.05	0.99	0.88	1.06	1.01	3.36
203002	1976-98	0.95	0.95	0.97	0.95	0.95	1.00	-0.01
238223	1965-96	0.90	1.02	1.05	0.89	1.02	1.07	-5.23
403206	1945-73	0.93	1.04	1.05	0.92	1.04	1.04	-1.76
406213	1959-96	0.93	1.05	1.00	0.91	1.04	1.01	3.23
608151	1955-98	0.93	1.05	1.04	0.86	1.05	1.09	-6.29
613002	1970-98	0.90	0.98	0.95	0.86	0.98	0.98	-11.34

Where CE = coefficient of efficiency for calibration period
Cr1 = ratio of modelled to historical runoff volume for calibration period
Cr2 = ratio of modelled to historical runoff volume for validation period
VE = coefficient of efficiency for validation period
Vr1 = ratio of modelled to historical CV of annual flows for calibration period
Vr2 = ratio of modelled to historical CV of annual flows for validation period
DBFI = percentage difference between baseflow indices derived from modelled and historical streamflow

5. Generation of Daily Rainfall Data

Two sets of one hundred replicates of 110 years of daily rainfall data (1889-1998) for each of the eight catchments were generated using the TPM and DMMS models. In applying the TPM model, the number of states for each month was based on the recommendations of Srikanthan and McMahon (1985); the adopted values are given in Table 5.1. These stochastically generated daily rainfall sequences are representative of spatially averaged catchment rainfalls, that are equally likely to occur under prevailing conditions over the historical data period.

For satisfactory model performance, the generated rainfall sequences should be statistically consistent with the characteristics of the historical rainfall that were used for rainfall generation. In this respect, models can be evaluated based on their capability to preserve various statistical parameters of the historical data. A successful model should preserve the monthly and annual characteristics in addition to preserving various daily characteristics. In this chapter, various statistical parameters used for model evaluation are described and the performance of the each model is evaluated accordingly.

5.1 Statistical Parameters Used for Model Evaluation

The performance of the daily generation models is evaluated using a number of statistical parameters. These include:

Annual statistics

- mean annual rainfall
- standard deviation of annual rainfall
- coefficient of skewness of annual rainfall
- serial correlation (lag one auto correlation)
- maximum annual rainfall (standardised by mean)
- minimum 2-year, 5-year and 10-year low rainfall sums
- mean annual number of wet days
- standard deviation of annual number of wet days

Monthly statistics (for each month of the year)

- mean monthly rainfall
- standard deviation of monthly rainfall
- coefficient of skewness of monthly rainfall
- serial correlation of monthly rainfall
- maximum monthly rainfall (standardised by mean)
- mean monthly number of wet days

Table 5.1 Number of states adopted with TPM Model

Catchment	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
112003	7	7	7	7	7	7	7	7	7	7	7	7
145102	7	7	7	7	7	7	7	7	7	7	7	7
203002	7	7	7	7	7	7	7	7	7	7	7	7
238223	6	6	6	6	6	6	6	6	6	6	6	6
403206	6	6	6	6	6	6	6	6	6	6	6	6
406213	6	6	6	6	6	6	6	6	6	6	6	6
608151	6	6	6	6	6	6	6	6	6	6	6	6
613002	6	6	6	6	6	6	6	6	6	6	6	6

Daily statistics

- mean daily rainfall (wet days) for each month
- standard deviation of daily rainfall (wet days) for each month
- coefficient of skewness of daily rainfall (wet days) for each month
- mean daily rainfall for solitary wet days for each month (WET 1)
- mean daily rainfall for wet days bounded only on one side by a wet day (WET 2)
- mean daily rainfall for wet days bounded on both sides by wet days (WET 3)
- mean dry spell length for each month (days)
- standard deviation of dry spell length (days)
- mean wet spell length for each month (days)
- standard deviation of wet spell length (days)
- correlation between rainfall depth and duration of wet spells over one or more days

The mean, standard deviation, coefficient of skewness and lag-1 autocorrelation are estimated from the following equations;

$$\bar{x} = \sum_{t=1}^{n} x_t$$

$$s = \sqrt{\frac{1}{(n-1)} \sum_{t=1}^{n} (x_t - \bar{x})^2}$$

$$g = \frac{n}{(n-1)(n-2)s^3} \sum_{t=1}^{n} (x_t - \bar{x})^3$$

$$r = \frac{1}{(n-1)s^2} \sum_{t=1}^{n-1} (x_{t+1} - \bar{x})(x_t - \bar{x})$$

In the above equations, x_t represents the annual, monthly or daily rainfall and n the number of data values.

5.2 Results

The various statistics derived from generated and historical rainfalls are compared in Appendix B. In Table B.1, mean values (average values of 100 replicates) of various annual statistics of generated rainfall using the two models are compared against the statistics of historical rainfall. Figure B.1 presents a comparison of average monthly statistics such as mean rainfall, standard deviation, skew coefficient, serial correlation, mean monthly number of wet days and maximum rainfalls for each month of the year. In Table B.2, various mean daily statistics of the generated rainfalls are compared against the corresponding daily statistics of historical rainfall. The statistics evaluated are mean, standard deviation and skew coefficient of daily rainfall (rainy days), mean of solitary wet days, mean of wet days with one or both sides bounded by wet days, mean and standard deviation of dry and wet spell lengths and correlation between rainfall depth and duration of wet spells.

Figures B.3, B.4 and B.5 present ‘box and whisker plots’ of annual, monthly and daily statistics respectively. The plots present the mean, 25% and 75% percentiles and the range (maximum and minimum) of the respective rainfall characteristic, derived from the 100 replicates of the generated rainfall sequences. The relative position of the respective historical values within the spectrum of variability of generated estimates indicates the model’s ability to preserve the rainfall characteristics of interest. Separate plots are given for January, April, July and October.

The plots presented in Appendix B provide a consistent basis for evaluation of the performance of the generation models with respect to preserving the historical characteristics. A model is considered to be performing satisfactorily if the generated and historical values are close to each other and if the historical value consistently lies within the 25% to 75% percentiles of the generated values. The plots are also indicative of any persistent bias in the generating algorithm.

5.3 Evaluation of Model Performance

Annual Statistics

Mean annual rainfall: Both models reproduce mean annual rainfall adequately. However, the TPM model has a slight tendency to overestimate the mean, although the differences are within 4%. The DMMS model overestimates the mean slightly for Qld and NSW catchments.

Standard deviation: The TPM model preserves the standard deviation very well by virtue of the adopted modification in the generating procedure (Boughton, 1999). On the other hand, the DMMS model has a consistent tendency to slightly underestimate the standard deviation. Except for catchment 112003, the underestimation of the standard deviation ranged from about 6 to 12 %.

Skew coefficient: Both models preserve skewness satisfactorily for some catchments but not for others. With the TPM model, historical values lie within the middle 50% of the generated values for 6 catchments, whereas DMMS model performs similarly for 4 catchments.

Serial correlation: Neither models preserves annual serial correlation; the serial correlation of generated rainfalls using both models is very close to zero.

Mean annual number of wet days: Both models preserve the annual number of wet days satisfactorily; the differences are within 2%.

Standard deviation of annual number of wet days: The two models perform similarly and considerably underestimate this statistic; the underestimation ranges from 30% to 70% across the catchments.

Monthly Statistics

Mean monthly rainfall: Both models preserve the monthly mean well. For two catchments, the TPM model slightly overestimates the mean during winter months.

Standard deviation: The DMMS model preserves the standard deviation very well. The performance of the TPM model is slightly erratic, but generally considered to be satisfactory for all catchments.

Skew coefficient: Neither model preserves the monthly skew, for the majority of the catchments.

Serial correlation: The DMMS model performs well; monthly variation of serial correlation is well modelled. On the other hand, the TPM model performs poorly in preserving monthly serial correlation; modelled values are fairly uniform over the year.

Maximum monthly rainfall: The performance of both models is generally satisfactory.

Average number of wet days: Both models preserve this statistic very well for all the catchments.

Daily Statistics

Mean daily rainfall: Both models perform satisfactorily for all the catchments. However, both models tend to overestimate the mean slightly for some catchments, although the differences are not significant.

Standard deviation: The TPM model performs exceptionally well. The DMMS model preserves the statistic adequately for the majority of catchments; the modelled values are overestimated for some catchments, particularly for those in Qld and NSW.

Skew coefficient: The TPM model performs satisfactorily for all the catchments. The performance of the DMMS model is generally satisfactory for Victorian and WA catchments; the modelled values are underestimated for other catchments.

WET 1: The performance of the TPM model is generally satisfactory. In contrast, the performance of the DMMS model is exceptionally poor as the modelled values are highly overestimated.

WET 2: The TPM modelled values are slightly overestimated, but are generally considered as reasonably modelled. The DMMS modelled values are highly overestimated.

WET 3: The TPM model preserves this statistic very well. The DMMS modelled values are underestimated for the majority of catchments.

Dry spell length - mean: Both models preserve this statistic very well.

Dry spell length - standard deviation: The two models perform satisfactorily for the majority of catchments but underestimate for Qld and NSW catchments.

Wet spell length - mean: Both models perform satisfactorily. TPM modelled values are slightly underestimated for some catchments.

Wet spell length - standard deviation: The two models perform in a similar manner. They are satisfactorily for the majority of catchments, although there is a tendency to underestimate the statistic for some catchments.

Correlation between wet spell depth and duration: The performance of the TPM model is generally satisfactory for all catchments. The DMMS model performs reasonably well for the majority of catchments, but tends to underestimate Qld and NSW catchments.

Table 5.2 summarises the performance of the two rainfall generation models. A further discussion of the model evaluation is given in Chapter 7.

Table 5.2: Comparison of performance of two rainfall generation models

Annual Statistics

Statistic	TPM Model	DMMS Model	Better
Mean annual rainfall	Satisfactory; with slight tendency to overestimate (<4%)	Satisfactory; slightly overestimates for Qld and NSW catchments	-
Standard deviation	Perfectly modelled	Consistently lower	TPM
Skew coefficient	Satisfactory for 6 catchments	Satisfactory for 4 catchments	-
Serial correlation (annual)	Nearly zero for all catchments; matches 6 catchments	Nearly zero for all catchments; matches 6 catchments	-
Mean annual number of wet days	Good modelling; differences are within 2%	Good modelling; differences are within 2%	-
Standard deviation of annual wet days	Poorly modelled; highly underestimated for all catchments	Same as for the TPM model	-

Monthly Statistics

Statistic	TPM Model	DMMS Model	Better
Mean monthly rainfall	Good modelling	Good modelling	-
Standard deviation	Reasonable modelling; slightly erratic for some catchments	Good modelling	DMMS
Skew coefficient	Not well modelled	Not well modelled	-
Serial correlation (monthly series)	Poorly modelled; modelled correlation is fairly uniform over the year	Good modelling; monthly variation is well modelled	DMMS
Maximum	Generally satisfactory	Generally satisfactory	-
Number of wet days for month	Good modelling for all catchments	Good modelling for all catchments	-

Daily Statistics (days with rainfall >0)

Statistic	TPM Model	DMMS Model	Better
Mean wet days rainfall	Good modelling; slightly overestimated for some catchments	Same as for TPM model	-
Standard deviation	Good modelling	Satisfactory modelling for majority of catchments; overestimated for others.	TPM
Skew coefficient of daily rainfall	Good modelling for all catchments	Satisfactory modelling for majority of catchments	TPM
WET 1	Satisfactory modelling	Poorly modelled; highly overestimated	TPM
WET 2	Slightly overestimated; but reasonably good modelling	Poorly modelled; highly overestimated	TPM
WET 3	Good modelling	Poorly modelled for majority of catchments; highly underestimated	TPM
Dry Spell length - mean	Good modelling for all catchments	Good modelling for all catchments	-
Dry Spell length - standard deviation	Good modelling, slightly underestimated for Qld and NSW catchments	Same as for TPM model	-
Wet Spell length - mean	Good modelling; slightly underestimated for some catchments	Good modelling	-
Wet Spell length - standard deviation	Good modelling for majority of catchments	Same as for TPM model	-
Correlation between wet spell depth and duration	Reasonably good modelling	Reasonably modelled for some catchments; underestimated for others	TPM

6. Simulation of Daily Streamflow

One of the major applications of rainfall generation is to synthesise long streamflow sequences and extend short flow records using a calibrated rainfall-runoff model; these data can then be used for developing planning models and designing hydrological and water resources systems. Uncertainty associated with such a procedure is twofold: uncertainty in rainfall generation and in rainfall-runoff modelling. The resultant streamflow data should have similar characteristics to the available recorded data.

In this study, the two rainfall generation models are evaluated to assess whether they can be used to derive flow sequences satisfactorily, preserving important statistical properties and flow characteristics. It is postulated that if the rainfall generation model can preserve the rainfall characteristics that are important in synthesising runoff, the resultant streamflow sequences, in turn, would have their inherent characteristics preserved. The evaluation procedure involves the use of a calibrated SIMHYD rainfall-runoff model for each catchment to:

- derive a daily streamflow sequence (1890-1998) from historical rainfall;
- derive 100 replicates of daily streamflow sequences from generated rainfall using TPM model;
- derive 100 replicates of daily streamflow sequences from generated rainfall using DMMS model;

Each replicate represents 109 years of data after discarding the first year of modelled flow. The description of the SIMHYD model and calibrated catchment parameters are given in Chapter 4.

The rainfall generation models are then evaluated by comparing various performance measures of streamflow derived from historical rainfall against streamflow synthesised from generated rainfall. The adopted measures are:

- annual, monthly and daily statistical properties of daily streamflow;
- daily flow duration curves;
- event parameters (eg. flow volume and peak) of selected events;

The evaluation procedure ignores uncertainty associated with the rainfall-runoff model.

6.1 Evaluation Based on Statistical Properties of Streamflow

The mean, standard deviation and skew coefficient that are derived from annual, monthly and daily time scales are the primary statistical parameters used for evaluation of the models. In addition, annual and monthly serial correlations of streamflow are also considered.

The various statistics computed from modelled streamflows via generated and historical rainfalls are compared in Appendix C. In Table C.1, mean values (average values of 100 replicates) of various annual statistics of streamflow derived from generated rainfall are compared against the statistics of streamflow derived from historical rainfall. Figure C.1 presents a comparison of average monthly statistics such as mean flow, standard deviation, skew coefficient, serial correlation and maximum flow for each month of the year. In Figure C.2, means, standard deviations and coefficients of skewness of daily streamflow derived from historical and generated rainfall are compared.

Figures C.3, C.4 and C.5 present “box and whisker plots” of annual, monthly and daily statistics respectively. The plots present the mean, 25% and 75% percentiles and the range (maximum and minimum) of the respective statistics, calculated from the 100 replicates of the streamflow sequences that are derived from generated rainfall. The ‘historical’ value is compared against the spread of ‘generated’ values. Separate plots are given for January, April, July and October.

The performance of the two rainfall generation models with respect to preserving statistical properties of derived streamflow is summarised in Table 6.1.

Table 6.1 Evaluation of statistical properties of streamflow derived from generated rainfall

Annual Statistics

Statistic	**TPM + SIMHYD Models**	**DMMS + SIMHYD Models**	**Better**
Mean annual runoff	Satisfactory modelling for all catchments	Satisfactory modelling for all catchments	-
Standard deviation	Satisfactory modelling for all catchments	Slightly underestimated for all catchments	TPM
Skew coefficient	Poorly modelled; only one catchment within middle 50% of generated values	Modelling poor to reasonable; four catchments within middle 50% of generated values	DMMS
Serial correlation (annual)	Poorly modelled; nearly zero for all catchments	Poorly modelled; nearly zero for all catchments	-

Monthly Statistics

Statistic	**TPM + SIMHYD Models**	**DMMS + SIMHYD Models**	**Better**
Mean monthly runoff	Good modelling for all catchments	Good modelling; slightly overestimated for two catchments	-
Standard deviation	Satisfactory modelling	Satisfactory modelling	-
Skew coefficient	Poorly modelled	Poorly modelled; values generally tend to be lower.	-
Serial correlation (monthly series)	Satisfactorily modelled for 2-3 catchments; varying success for other catchments: fair to poor	Same as for TPM	-
Monthly maximum	Not satisfactory; months with higher maximum flows tend to be underestimated	Same as for TPM	-

Daily Statistics (days with runoff >0)

Statistic	**TPM + SIMHYD Models**	**DMMS + SIMHYD Models**	**Better**
Mean (days with runoff >0)	Good modelling; very similar to monthly performance as very few zero flows are accounted	Good modelling	-
Standard deviation	Satisfactory modelling for all catchments	Satisfactory modelling for all catchments	-
Skew coefficient	Poorly modelled for majority of catchments	Poorly modelled for majority of catchments	-

6.2 Evaluation Based on Daily Flow Duration Curves

In this evaluation, two average daily flow duration curves derived from flows based on TPM and DMMS generated rainfalls are compared against a flow duration curve of modelled flows from historical rainfall. A daily flow duration curve was derived for each replicate and flow quantiles were computed for a range of exceedances from 1% to 99%. An average curve was then established using average quantiles over 100 replicates at desired probability of exceedances. The results are shown in Figure C.6 (Appendix C) as log-normal probability plots.

The results indicate that the flow duration curves derived from generated rainfall match very well with the curves derived from historical rainfall for all eight catchments. The curves that are based on generated rainfall using TPM and DMMS models are not significantly different.

From the results it can be concluded that both rainfall generation models perform satisfactorily in synthesising streamflow sequences, provided that the same calibrated rainfall-runoff model is used. Any differences in the characteristics of the rainfalls generated from the two models have little impact on the flow duration curve of synthesised flow.

6.3 Evaluation Based on Event Modelling

Evaluation of flow duration curves provides a general overview of the modelling performance over the whole range of daily streamflow values. However, it is also important to assess the adequacy of the modelling approach in estimating streamflow during high rainfall events under varying antecedent conditions. In this study, limited testing was carried out to evaluate whether there is a significant impact on event rainfall characteristics due to use of different rainfall generation models in the procedure.

Three-day isolated rainfall events were extracted from historical daily rainfall records and from 100 replicates of generated rainfall sequences to satisfy following constraints:

- total rainfall four days prior to the start of the event is less than 0.2 mm;
- total rainfall four days after the end of the event is less than 0.2 mm;
- total rainfall during the three day event is greater than 5 mm;
- daily rainfall for each day during the event is greater than 1 mm.

The resulting streamflow volumes and peak daily flows corresponding to these rainfall events were then extracted from the synthesised daily streamflow sequences derived from historical and generated rainfall. The streamflow event was assumed to last over 7 days from the start of the rainfall event to four days after the end of the rainfall event.

The mean, standard deviation and coefficient of skew of event flow volumes and peak flow rates were then computed for the events based on historical rainfall and those based on generated rainfall respectively. The 'generated' statistics were based on all events extracted from 100 replicates, whereas 'historical' statistics were based on a single sequence of 110 years of data. The 'generated' statistics for two models are compared against 'historical' statistics in Figure C.7 (Appendix C). The statistical properties for event flow volumes and peaks derived from different modelling approaches are evaluated in Table 6.2.

Table 6.2 Evaluation of statistical properties of 3-day event streamflow volumes and peaks

Event flow volume

Statistic	**TPM + SIMHYD Models**	**DMMS + SIMHYD Models**	**Better**
Mean	Satisfactory modelling for all catchments	Satisfactory modelling except for two catchments whose values are overestimated	TPM
Standard deviation	Modelling generally satisfactory; slightly overestimated for two catchments	Modelling generally satisfactory except for two catchments whose values are highly overestimated	TPM
Skew coefficient	Poorly modelled; 'generated' event values are highly overestimated	Poorly modelled; 'generated' event values are overestimated	DMMS

Event flow peak

Statistic	**TPM + SIMHYD Models**	**DMMS + SIMHYD Models**	**Better**
Mean	Satisfactory modelling for all catchments	Satisfactory modelling except for two catchments whose values are highly overestimated	TPM
Standard deviation	Overestimated for three catchments; modelling satisfactory for other catchments	Highly overestimated for three catchments; modelling satisfactory for other catchments	TPM
Skew coefficient	Modelling exceptionally poor; 'generated' event values are very highly overestimated	Poorly modelled; 'generated' event values are overestimated	DMMS

A further discussion of these results is given in Chapter 7.

7. Discussion of Results

The study concentrated on evaluating two daily rainfall generation models with respect to:

- preserving various annual, monthly and daily rainfall characteristics of historical;
- preserving various annual, monthly and daily streamflow characteristics when streamflow sequences are synthesised from the SIMHYD conceptual rainfall-runoff model using stochastically generated daily rainfall; daily, monthly and annual as well as event streamflow characteristics were evaluated.

7.1 Evaluation Based on Rainfall Characteristics

Both TPM and DMMS models incorporate adjustments to generating mechanisms to preserve important characteristics. Generally, it would not be possible to model satisfactorily all the statistics at various time scales. But it is imperative that important parameters such as mean and standard deviation of generated rainfalls are satisfactorily modelled at daily, monthly and annual time scales.

The results indicate that both models adequately preserve the mean and standard deviation of historical rainfall at annual, monthly and daily time scales. However, the TPM model has a tendency to slightly overestimate the mean for some catchments; the differences are usually within 4%. The TPM model simulates the standard deviation of annual rainfall well by virtue of an incorporated modification in the generating algorithm (Boughton, 1999). However, the same accuracy is not preserved at a monthly time scale, where the values deviated somewhat from the historical values, without any persistent bias. The annual standard deviation of DMMS generated rainfall is consistently lower than the corresponding historical values. The coefficient of skewness is adequately preserved at a daily scale by both models, but not at monthly and annual scales. Both models failed to preserve inter annual variability in the annual number of wet days. Overall, it can be concluded that both models preserve key statistics adequately, and there is no clear indication that one model outperforms the other in this respect.

By virtue of an adjustment to the generating algorithm, the DMMS model preserves satisfactorily the historical monthly serial correlation, in contrast to the poor performance of the TPM model in this respect. However, neither model is able to preserve the annual serial correlation.

A major difference in the performance of the two models is exhibited when the performance of the solitary, one side and both sides bounded wet day statistics, ie. WET 1, WET 2 and WET 3, is compared. The three statistics are well modelled by the TPM model for all the catchments tested. The performance of the DMMS model in this regard is exceptionally poor; the model highly overestimates historical WET 1 and WET 2 statistics and consistently underestimates the WET 3 statistic.

Dry spell and wet spell characteristics (mean and standard deviation of spell duration) are generally modelled satisfactorily by both models. Similarly, the annual and monthly mean numbers of wet days are also modelled well by both models. However, both models severely underestimate the standard deviation of the annual number of wet days. The underestimation is as high as 30-70% across the catchments tested. Modelling of the correlation between wet spell depth and duration is slightly better for the TPM model compared with the DMMS model.

The various plots in Appendix B indicate that the TPM model produces consistent results for all the catchments, ie. summer and winter dominant rainfall catchments alike. With the DMMS model, good results were obtained for VIC and WA catchments consistently, but the performance was slightly lower for Qld and NSW catchments.

7.2 Evaluation Based on Streamflow Characteristics

In this evaluation, characteristics of SIMHYD modelled streamflow from historical rainfall are taken as the reference. If these characteristics can be preserved by the modelled streamflows from rainfalls generated by TPM and DMMS models, then the rainfall generation models are considered to perform satisfactorily. It was shown that (Table 6.1) the mean and standard deviation, of synthesised streamflow are adequately modelled at daily, monthly and annual time scales irrespective of the model used for rainfall generation in the combined modelling approach. However, the coefficient of skew is poorly modelled at all time scales with both generation models.

The results indicate that there is no clear distinction between the two rainfall generation models in the overall model performance with respect to preserving streamflow characteristics. The characteristics of the resultant streamflow sequences appear to be very similar whatever the rainfall generation model used in the overall modelling approach. In particular, the deficiency in preserving WET1, WET2 and WET3 characteristics by the DMMS model appears to have little impact on the final outcome.

It was shown that the flow duration curves derived from generated rainfall match very well with the curves derived from historical rainfall for all eight catchments (Figure C.6). The curves that are based on generated rainfall using TPM and DMMS models are not significantly different. From the results it can be concluded that both rainfall generation models satisfactorily perform in synthesising streamflow sequences using the same calibrated rainfall-runoff model. Any differences in the rainfall characteristics of the rainfalls generated from two models have little impact on the flow duration curve of synthesised flow.

It should be noted that, in the above evaluation, uncertainties associated with the calibrated SIMHYD model are ignored by comparing the results against characteristics of the modelled streamflow from historical rainfall instead of using characteristics of recorded streamflow directly. Figure A.1 illustrates the uncertainty associated with SIMHYD model itself in which flow duration curves for streamflows from historical rainfall is directly compared against those derived from the historical streamflow. These figures show significant differences between the two curves for most of the catchments. This highlights the importance of modelling accuracy at a daily scale and emphasises the need for improved performance in rainfall-runoff modelling.

It is evident from the results that the adequacy of the rainfall-runoff model is more important than the performance of the rainfall generation model in the overall procedure of synthesising streamflow sequences. Both rainfall generation models perform satisfactorily within their scope in the overall procedure.

The flow duration curves provide only a general overview of the model performance over the entire range of streamflow values. The ability of the model to preserve various characteristics during larger events is considered to be more important. The limited testing carried out during this study indicates the TPM preserves mean and standard deviation of event streamflow volumes and peaks flows satisfactorily and more consistently. With the DMMS model, the key statistical event parameters, the mean and standard deviation, are modelled satisfactorily for the majority of catchments; however, the statistics for two catchments in Qld and NSW are highly overestimated. The coefficient of skew is not satisfactorily modelled using either model for rainfall generation. Overall, the use of TPM model for rainfall generation provides slightly improved and more consistent results across the catchments tested.

8. Conclusions

The study concentrated on evaluating the performance of two daily rainfall generation models, namely, the Transition Probability Matrix (TPM) model with Boughton's correction and a simplified Daily and Monthly Mixed (DMMS) model, by applying them to eight catchments located in different parts of Australia. The models were assessed on their ability to preserve daily, monthly and annual characteristics of historical rainfall. As an important process of evaluation, generated rainfall sequences were translated to daily streamflow sequences using a calibrated rainfall-runoff model (SIMHYD). The models were then assessed in relation to their ability to preserve appropriate streamflow characteristics of that modelled from historical rainfall.

Both models preserve the mean and standard deviation of historical rainfall adequately at daily, monthly and annual time scales. The modelling of the coefficient of skewness is less successful with both models. However, it was shown that the TPM model is more consistent and adequately preserves other daily rainfall characteristics, specifically, the characteristics of WET1, WET2 and WET3 satisfactorily, whereas the DMMS model does not reproduce these statistics. The event modelling also indicated that the TPM model is more consistent in preserving the characteristics of streamflows produced by putting the generated rainfall through a rainfall-runoff model.

Overall, it can be concluded that the TPM model is a slightly better model with a greater consistency in preserving different daily, monthly and annual characteristics of historical rainfall and having the ability to model catchments from different climates with the same degree of success. The major drawback of this model over the DMMS model is its inability to preserve monthly correlation.

The following conclusions can be drawn from the results of this study:

- Both models preserve most of the statistical characteristics of historical rainfall satisfactorily at daily, monthly and annual levels.
- The TPM model is the slightly better model with a greater consistency in preserving different daily, monthly and annual characteristics of historical rainfall and having ability to model catchments of different characteristics with the same degree of success.
- The DMMS model simulates poorly the rainfall amounts on different types of wet days (solitary wet day, wet days bounded on one side by a wet day and wet days bounded on both sides by wet days). The TPM model preserves these characteristics adequately.
- The major drawback of the TPM model over the DMMS model is its inability to preserve correlation between monthly rainfalls; the DMMS model preserves this statistic satisfactorily.
- There is no clear distinction between the two rainfall generation models in the overall performance of the rainfall-runoff model with respect to preserving characteristics of daily, monthly and annual streamflow modelled using the SIMHYD rainfall-runoff model. Both rainfall generation models perform satisfactorily.
- The adequacy of the rainfall-runoff model is more important than the performance of the rainfall generation model in the overall procedure of synthesising daily streamflow sequences.
- The rainfall-runoff modelling for synthesised streamflow indicated that the TPM model is more consistent in preserving various characteristics of event flow volumes and peak flow rates.

In conclusion, if the use of stochastic data is to obtain monthly flows, there is no difference between the two models and either model can be used.

9. References

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Appendix A: Calibration of SIMHYD Model Daily Flow Duration Curves

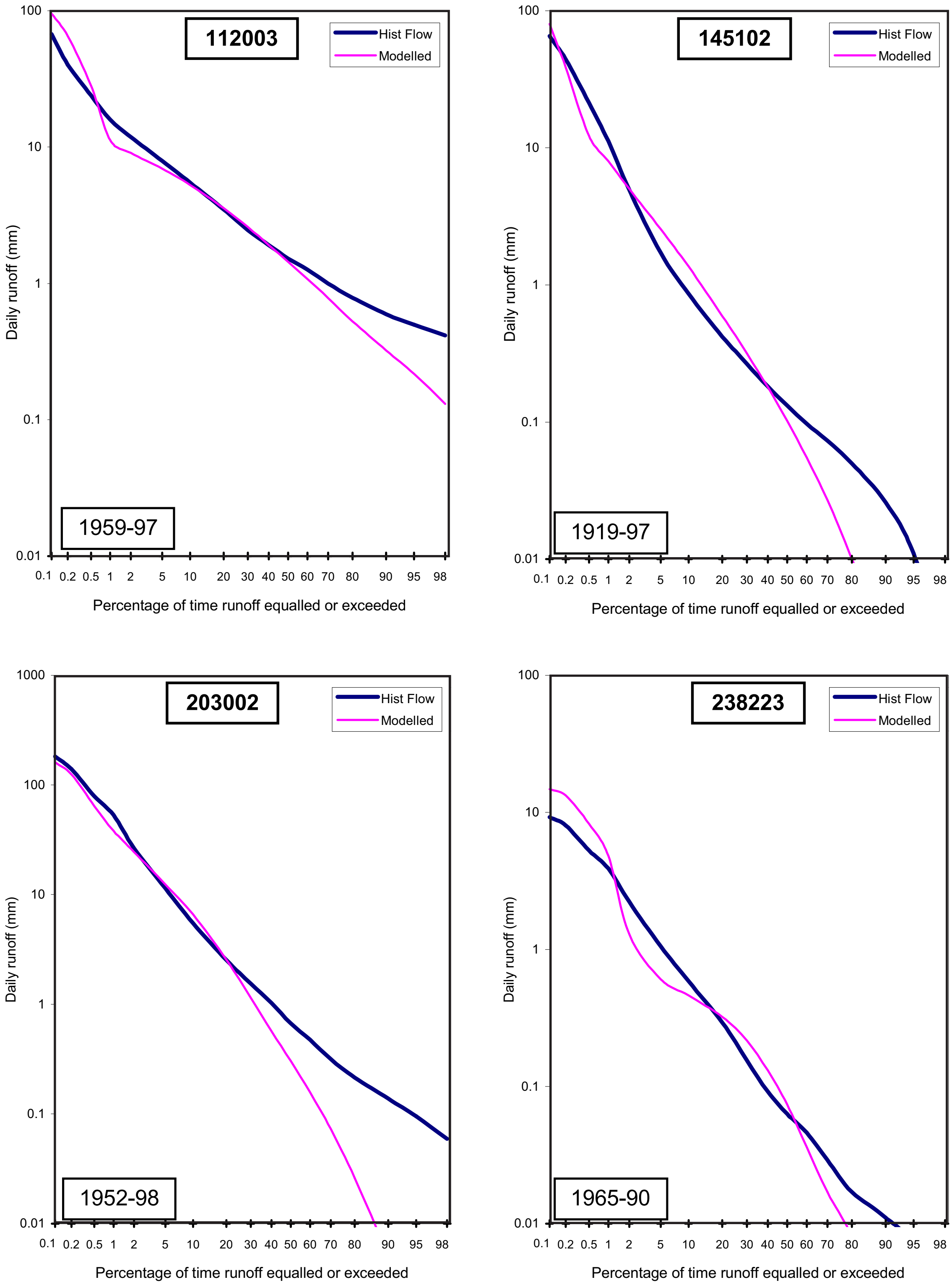


Figure A.1 Comparison of flow duration curves: SIMHYD modelled streamflow from historical rainfall against historical streamflow

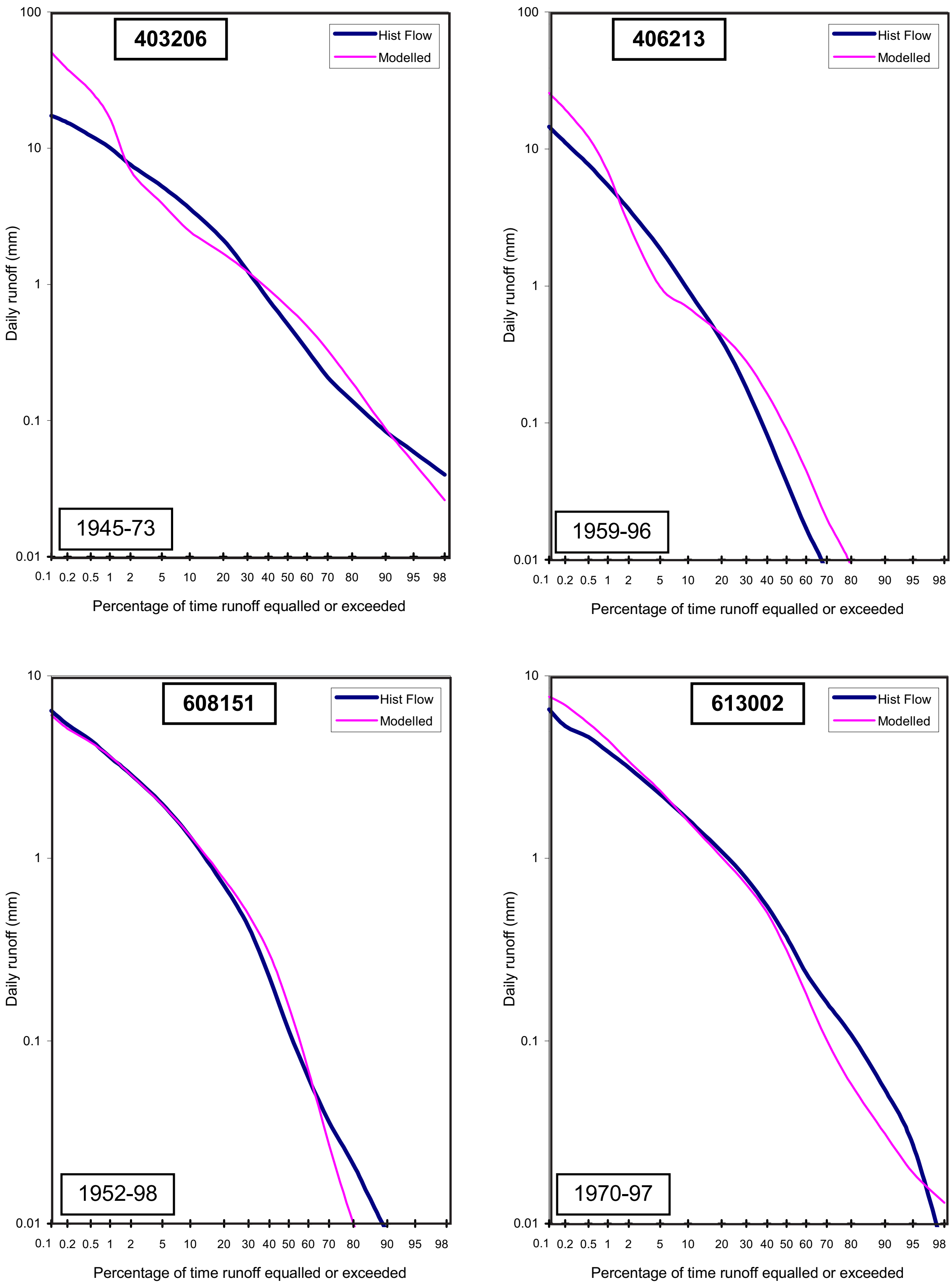


Figure A.1 Comparison of flow duration curves: SIMHYD modelled streamflow from historical rainfall against historical streamflow (continued)

Appendix B: Comparison of Rainfall Statistics

Table B.1 Annual Statistics for generated rainfall using TPM and DMMS models

ANNUAL STATISTICS (mean values)

Catchment	Case	Annual (mm)	StdDev (mm)	Skew	R1	Min	Max	2-year Low	5-year Low	10-year Low	Number of wet days Mean	Number of wet days StdDev
112003	Historical	1909	476	0.35	-0.05	0.38	1.58	1.32	3.75	8.52	198	39.7
	TPM	1946	479	0.61	-0.01	0.48	1.75	1.24	3.89	8.59	195	18.2
	DMMS	1931	476	0.53	-0.01	0.48	1.74	1.24	3.83	8.53	196	17.8
145102	Historical	1320	389	0.70	0.18	0.44	2.00	0.99	3.33	8.10	195	27.3
	TPM	1356	392	0.74	0.00	0.42	1.92	1.16	3.67	8.36	190	15.9
	DMMS	1367	355	0.82	0.01	0.47	1.83	1.24	3.90	8.68	190	16.9
203002	Historical	2073	612	0.74	0.21	0.42	1.82	1.19	3.33	7.15	165	23.1
	TPM	2096	614	0.49	-0.01	0.37	1.85	1.09	3.58	8.19	163	15.2
	DMMS	2129	537	0.67	0.03	0.48	1.77	1.25	3.84	8.56	163	15.6
238223	Historical	710	123	-0.10	-0.03	0.52	1.41	1.42	4.34	9.17	180	22.7
	TPM	736	125	0.82	0.05	0.64	1.51	1.49	4.28	9.22	175	14.1
	DMMS	711	115	0.25	0.00	0.63	1.45	1.47	4.19	8.95	179	14.1
403206	Historical	1411	328	0.51	0.01	0.50	1.69	1.30	4.18	8.66	157	25.7
	TPM	1420	329	0.32	0.00	0.47	1.65	1.23	3.84	8.50	154	14.2
	DMMS	1415	275	0.24	0.00	0.54	1.53	1.37	4.04	8.75	156	14.3
406213	Historical	770	172	-0.25	0.02	0.50	1.56	1.10	3.95	8.32	200	19.5
	TPM	803	175	0.85	0.04	0.55	1.67	1.35	4.09	8.96	194	14.2
	DMMS	774	151	0.35	-0.01	0.56	1.56	1.38	4.04	8.80	198	14.7
608151	Historical	1063	175	0.75	0.04	0.68	1.66	1.49	4.30	8.78	200	47.6
	TPM	1086	177	0.59	0.01	0.63	1.48	1.50	4.28	9.16	196	13.8
	DMMS	1062	159	0.09	-0.01	0.63	1.41	1.48	4.22	9.00	199	14.0
613002	Historical	1159	212	0.50	0.04	0.64	1.52	1.49	3.80	8.43	132	24.1
	TPM	1170	213	0.37	0.00	0.58	1.52	1.40	4.12	8.89	131	12.8
	DMMS	1159	199	0.18	0.00	0.61	1.47	1.45	4.14	8.88	132	12.8

Average values from 100 replicates

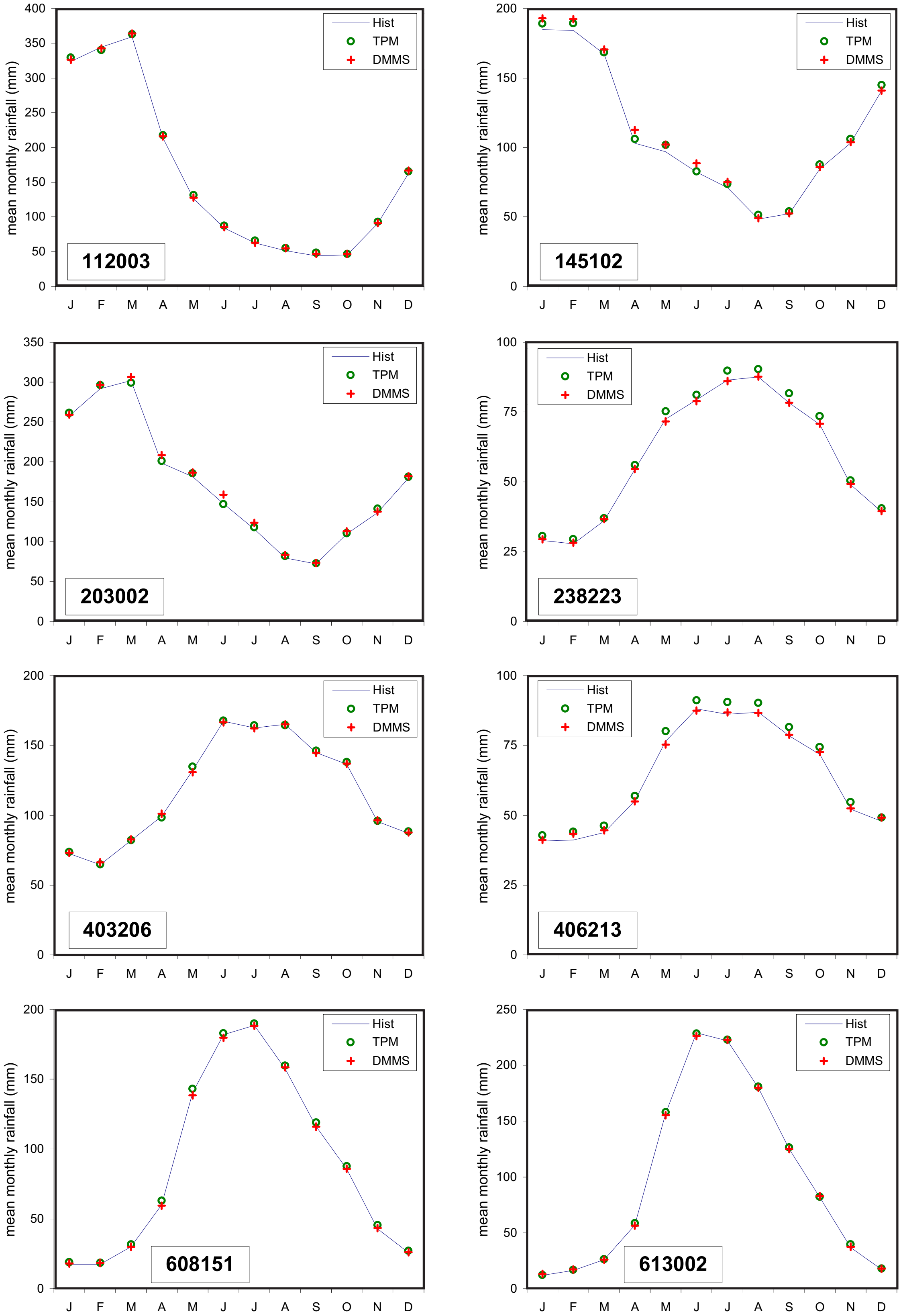


Figure B.1 Monthly statistics for generated rainfall using TPM and DMMS models
(a) Mean monthly rainfall

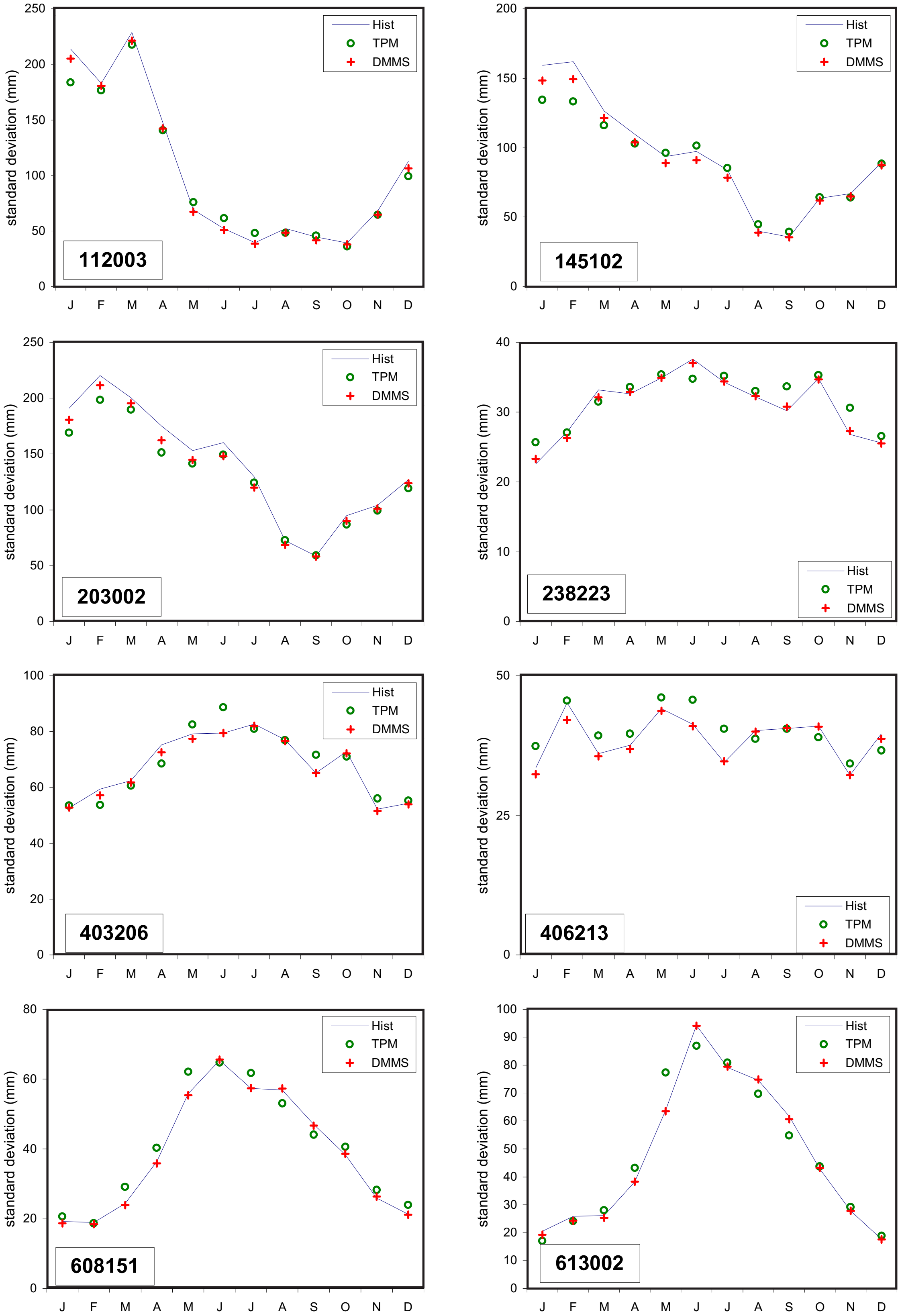


Figure B.1 Monthly statistics for generated rainfall using TPM and DMMS models
(b) Standard deviation of monthly rainfall

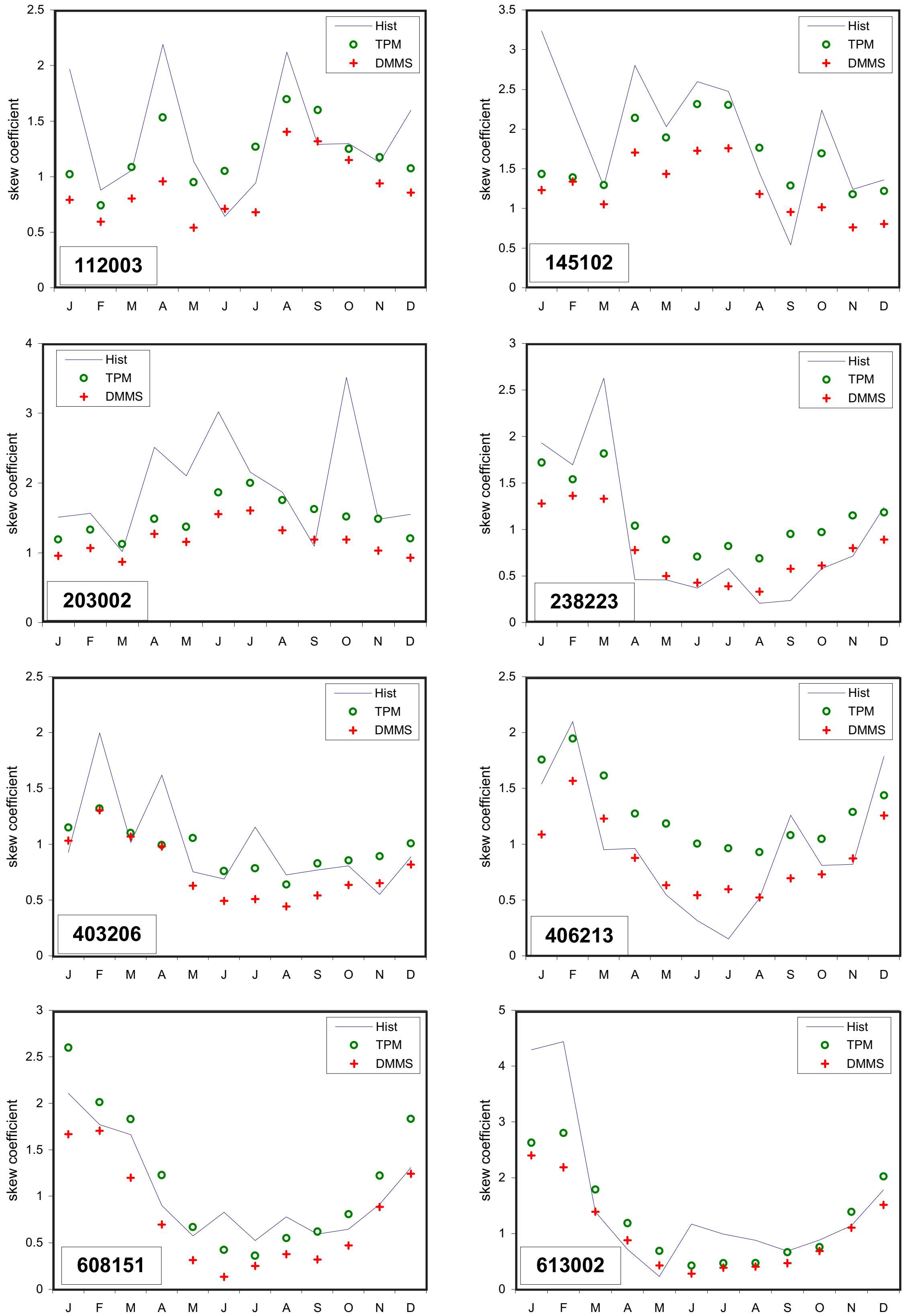


Figure B.1 Monthly statistics for generated rainfall using TPM and DMMS models
(c) Skew coefficient of monthly rainfall

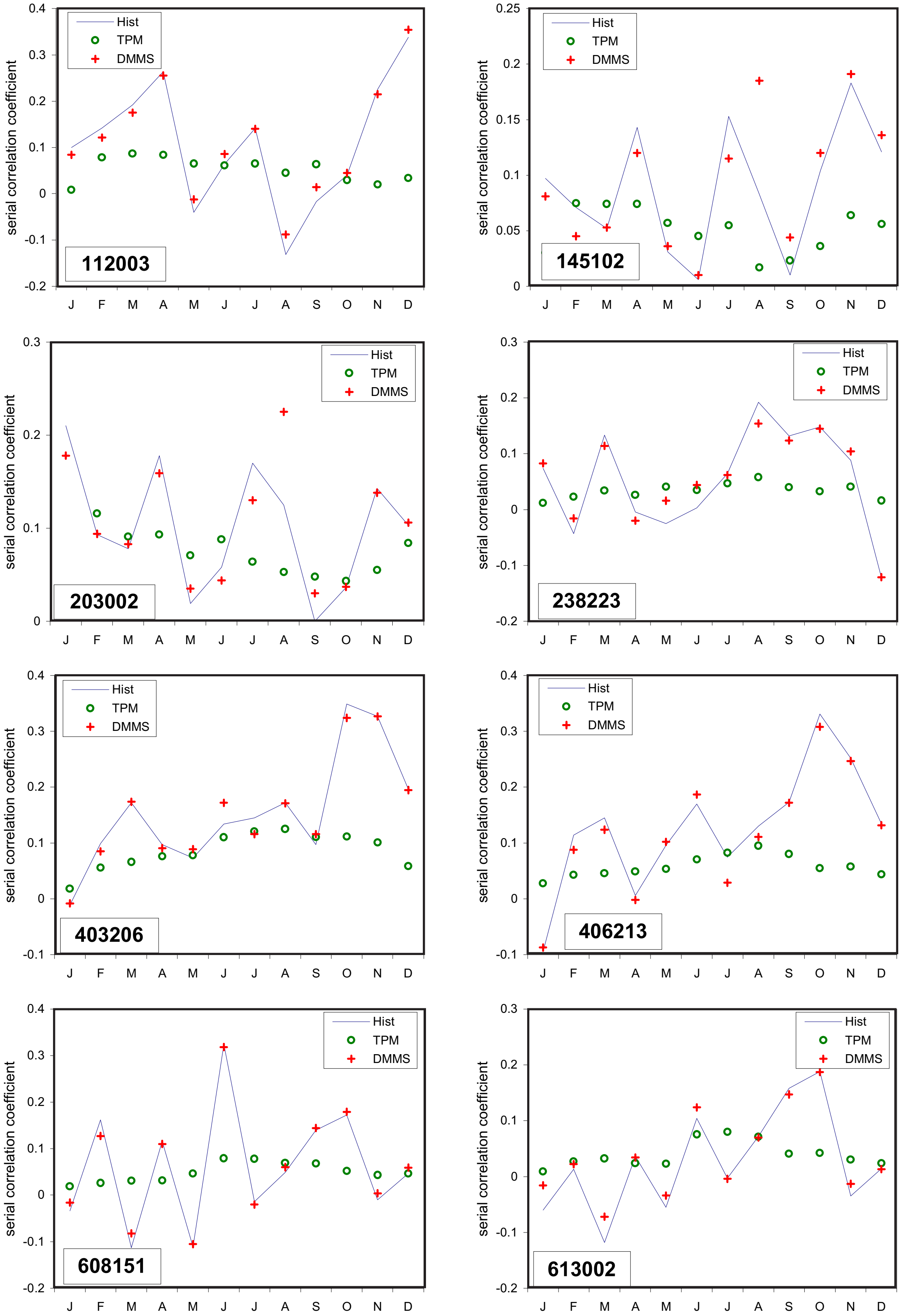


Figure B.1 Monthly statistics for generated rainfall using TPM and DMMS models
(d) Serial correlation of monthly rainfall

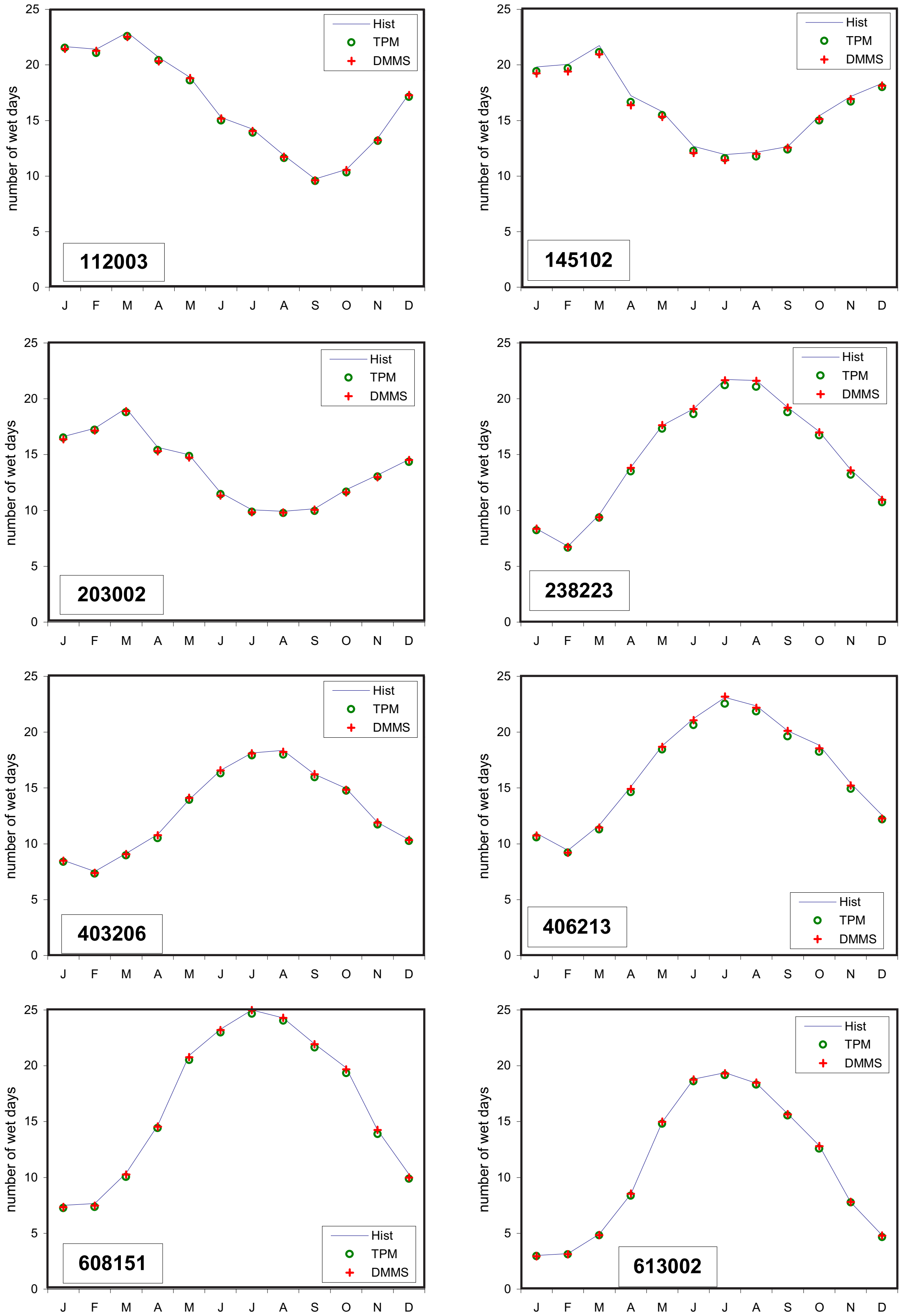


Figure B.1 Monthly statistics for generated rainfall using TPM and DMMS models
(e) Average number of wet days for each month

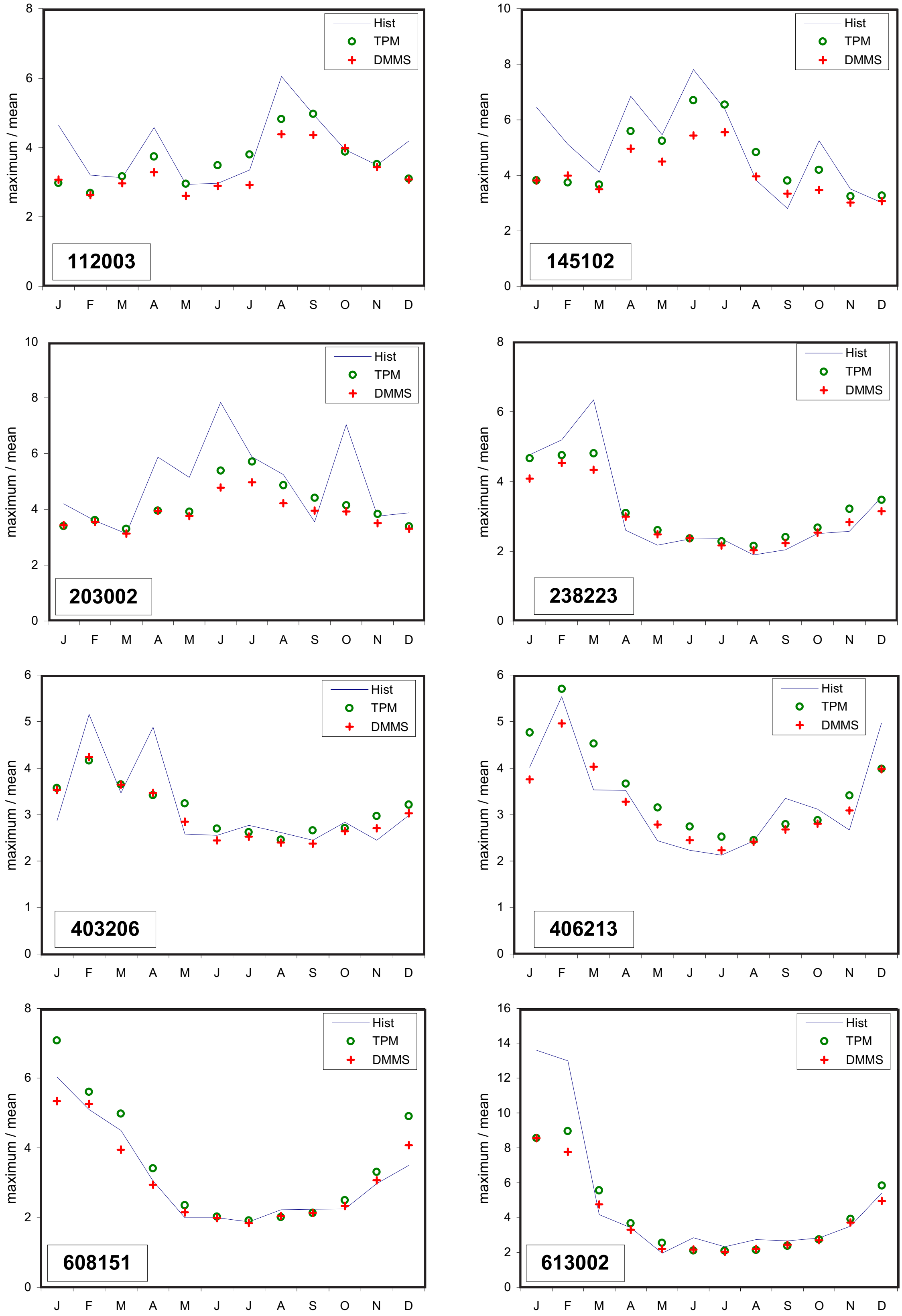


Figure B.1 Monthly statistics for generated rainfall using TPM and DMMS models
(f) Monthly maximum rainfall (standardised by mean)

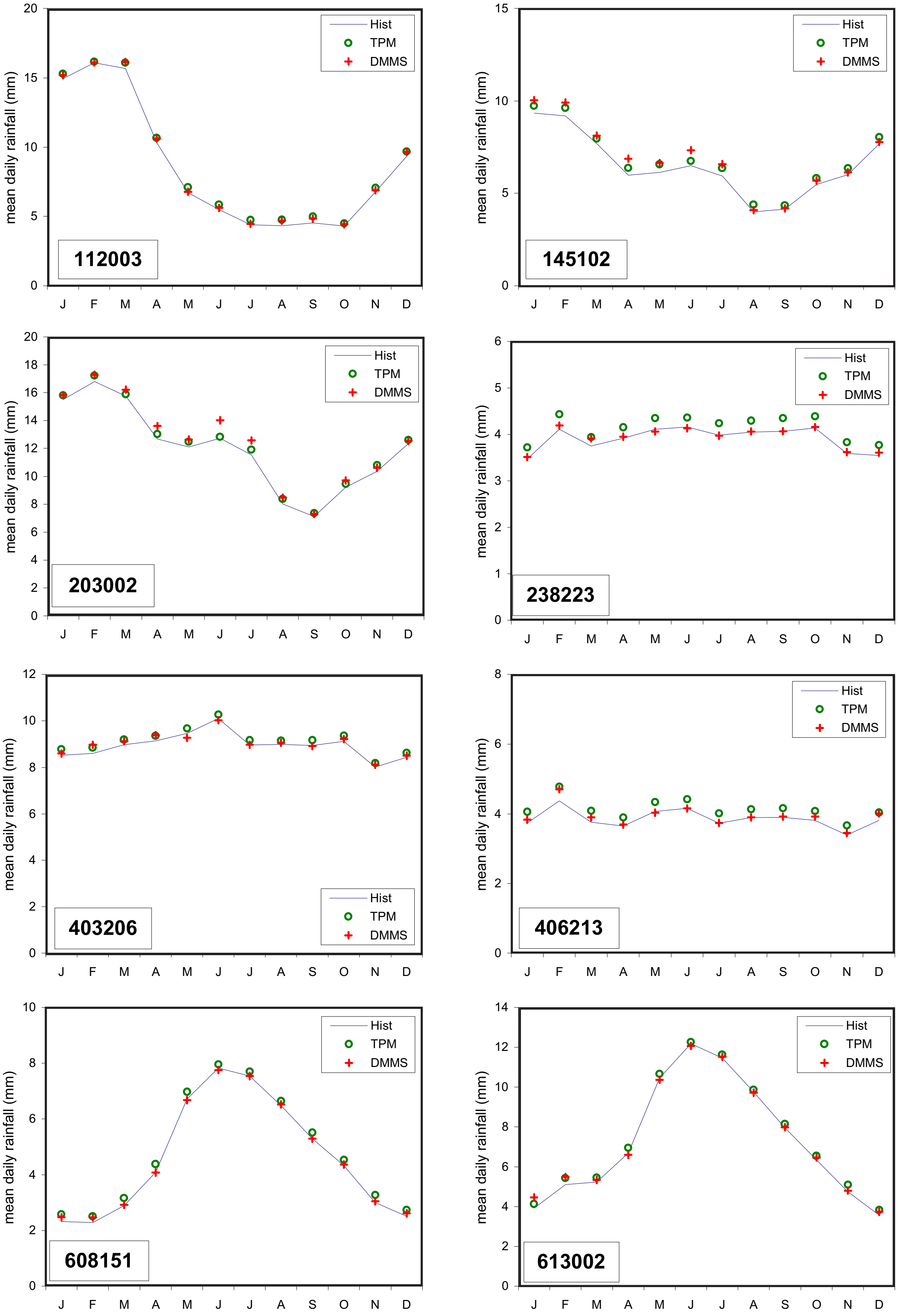


Figure B.2 Daily statistics for generated rainfall using TPM and DMMS models
(a) Mean daily rainfall

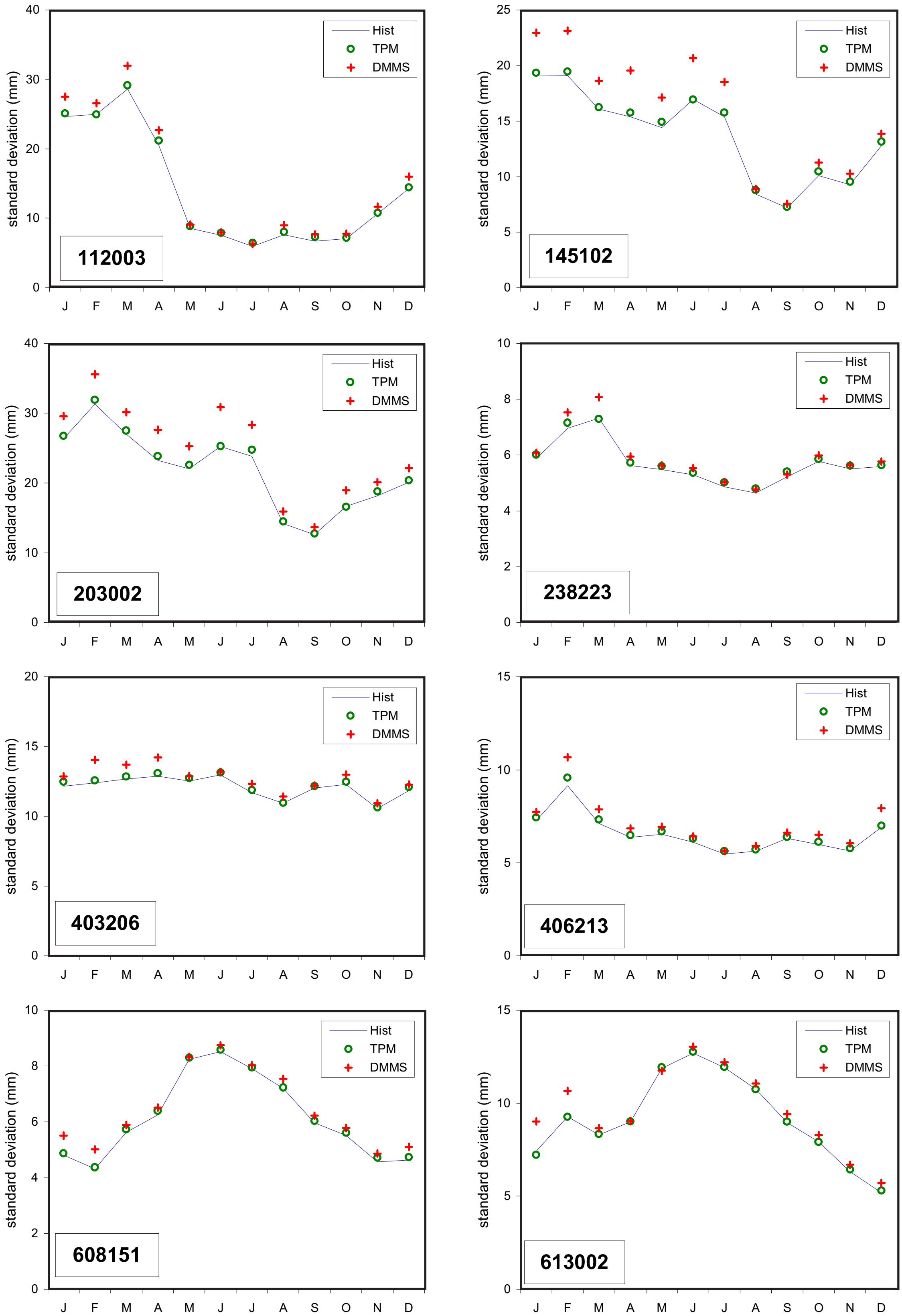


Figure B.2 Daily statistics for generated rainfall using TPM and DMMS models
(b) Standard deviation of daily rainfall

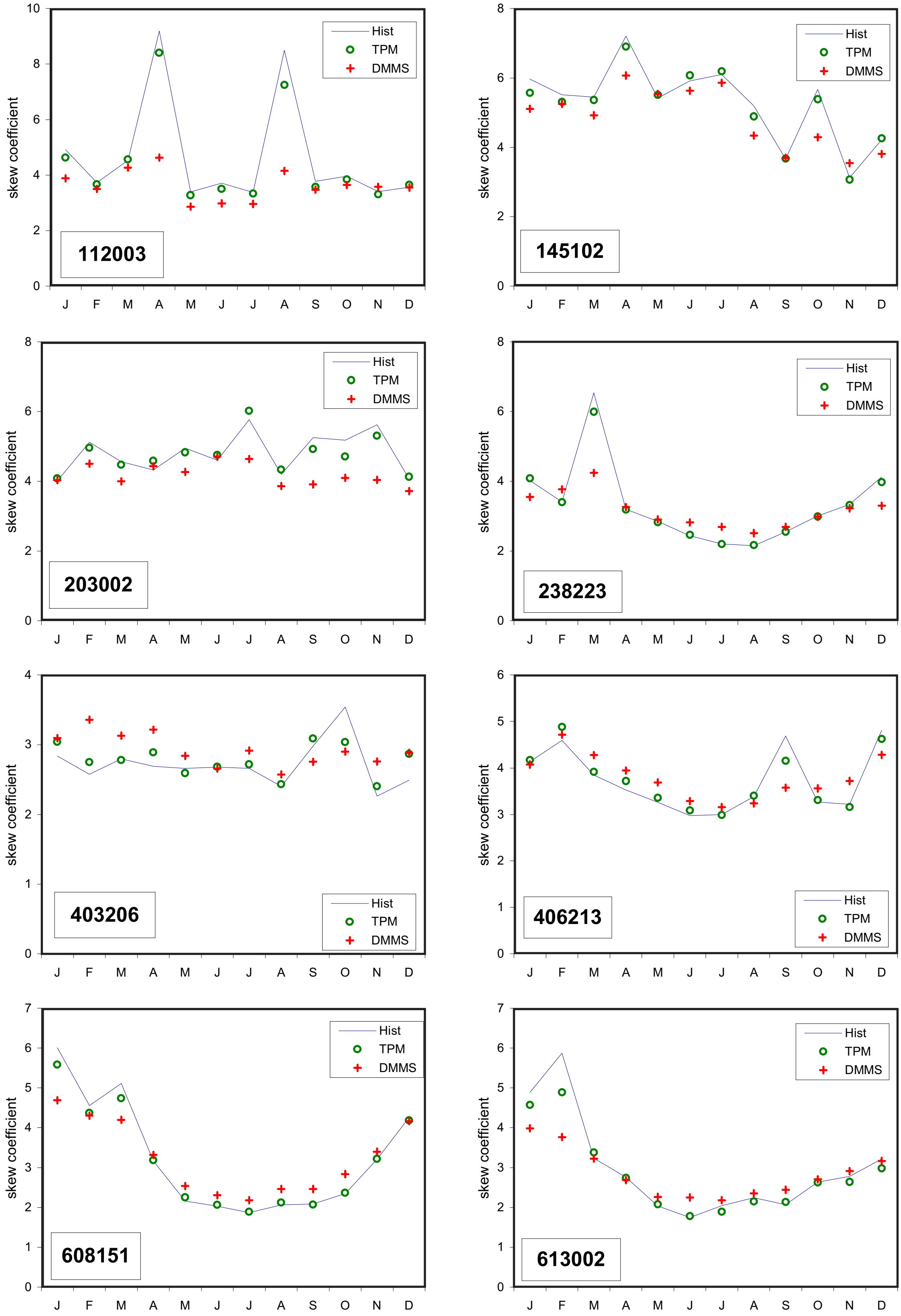


Figure B.2 Daily statistics for generated rainfall using TPM and DMMS models
(c) Skew coefficient of daily rainfall

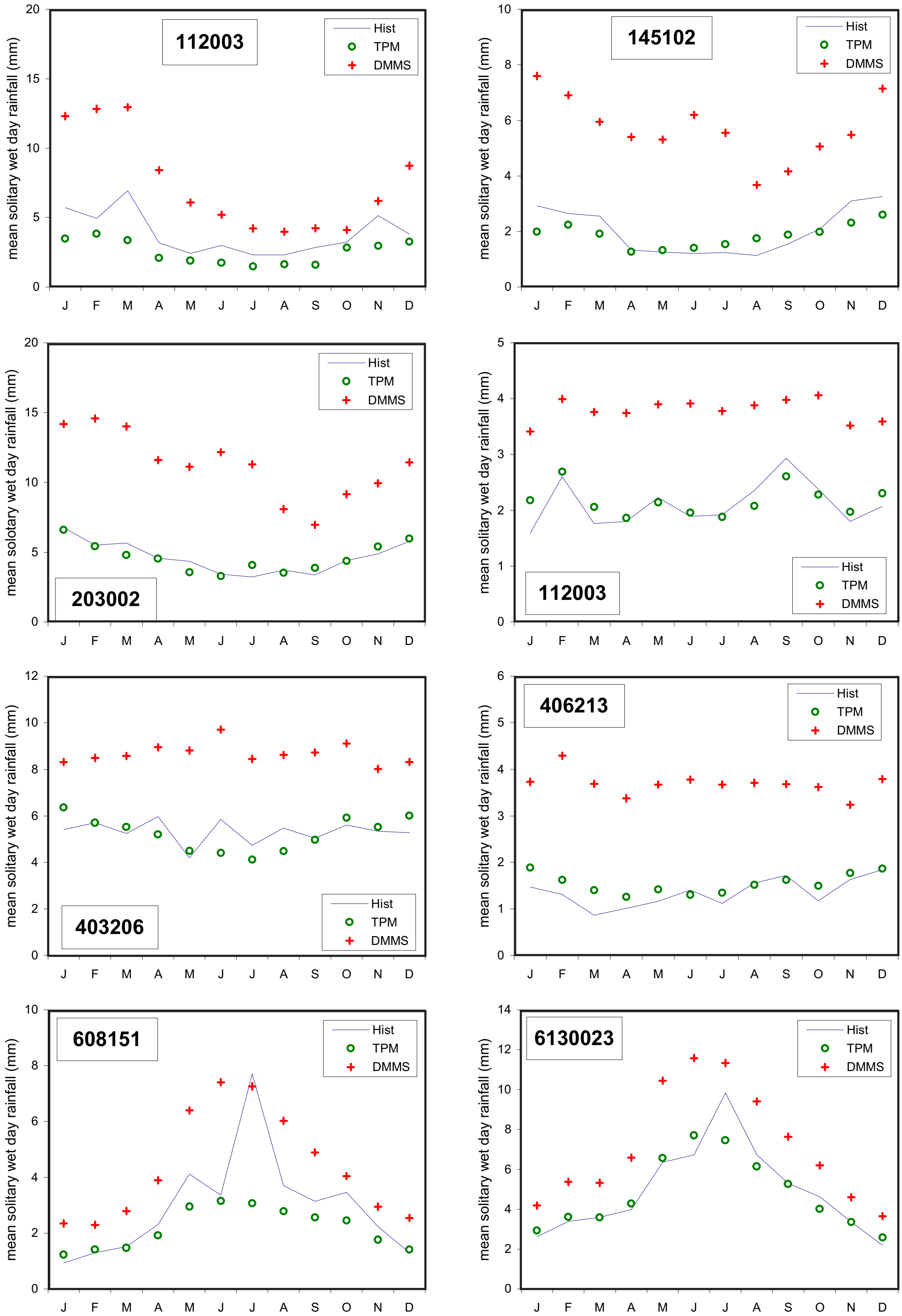


Figure B.2 Daily statistics for generated rainfall using TPM and DMMS models
(d) Mean daily rainfall of solitary wet days (WET 1)

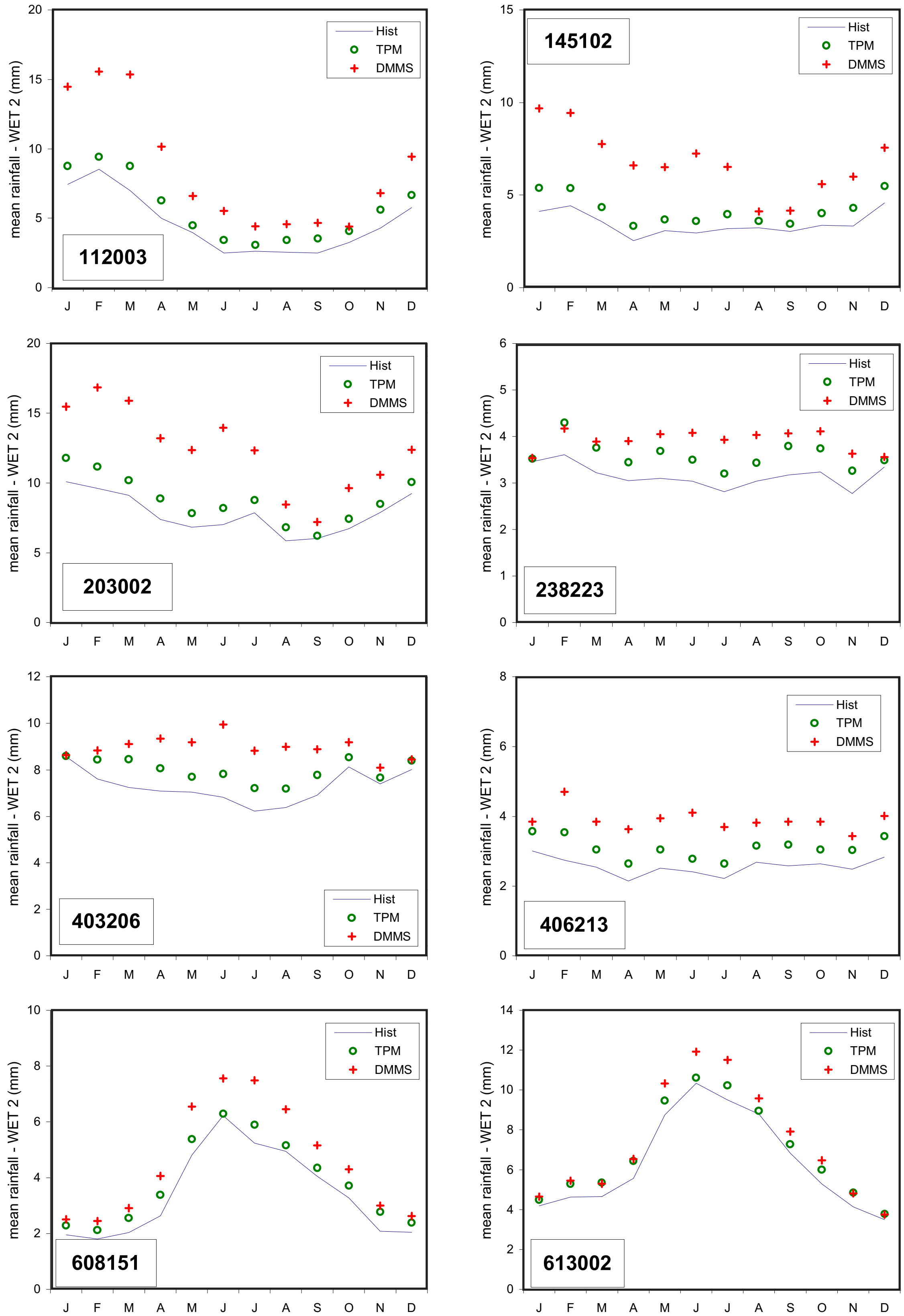


Figure B.2 Daily statistics for generated rainfall using TPM and DMMS models
(e) Mean daily rainfall of wet days with one side bounded by a wet day (WET 2)

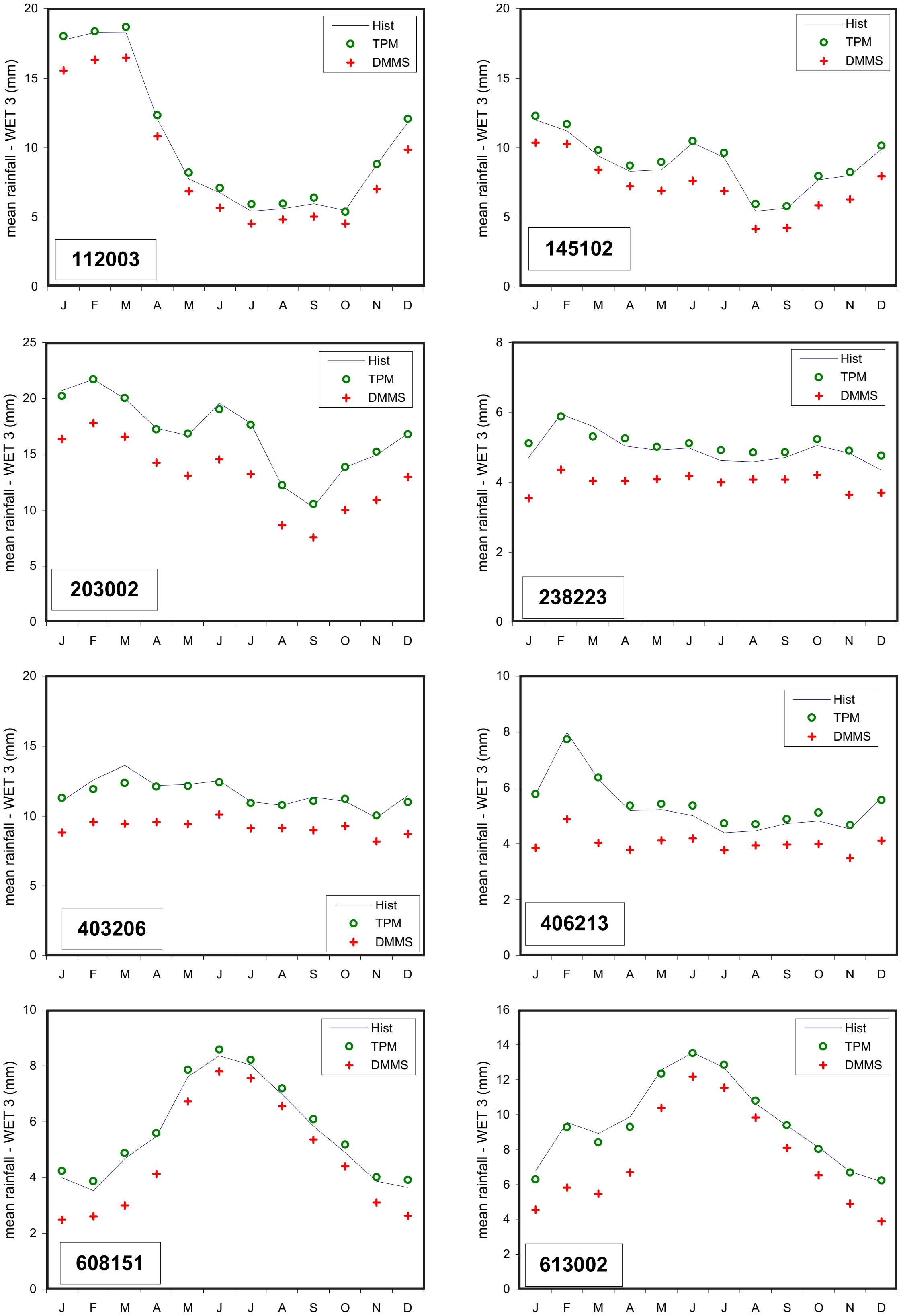


Figure B.2 Daily statistics for generated rainfall using TPM and DMMS models
(f) Mean daily rainfall of wet days with both sides bounded by wet days (WET 3)

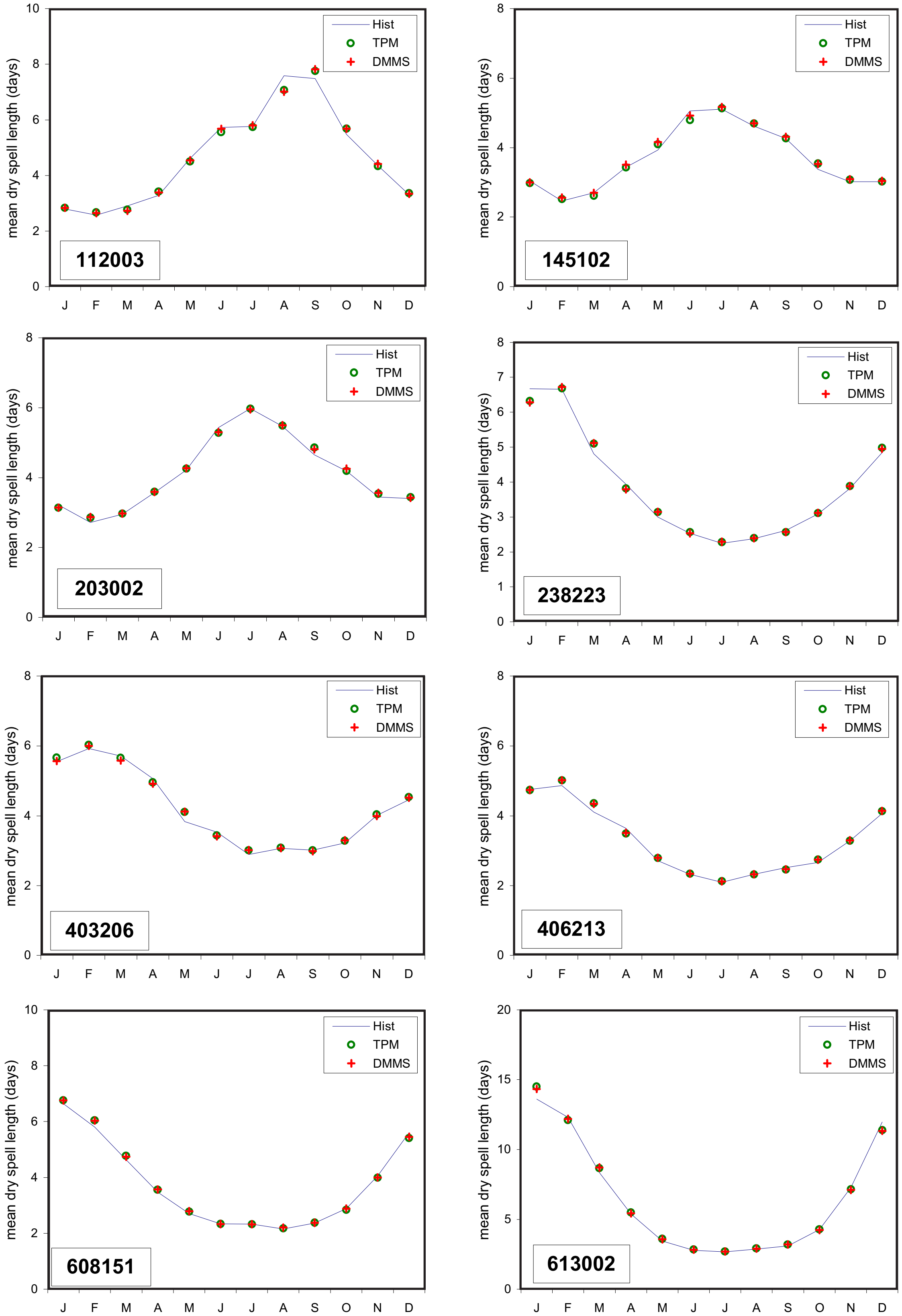


Figure B.2 Daily statistics for generated rainfall using TPM and DMMS models
(g) Mean dry spell length (days)

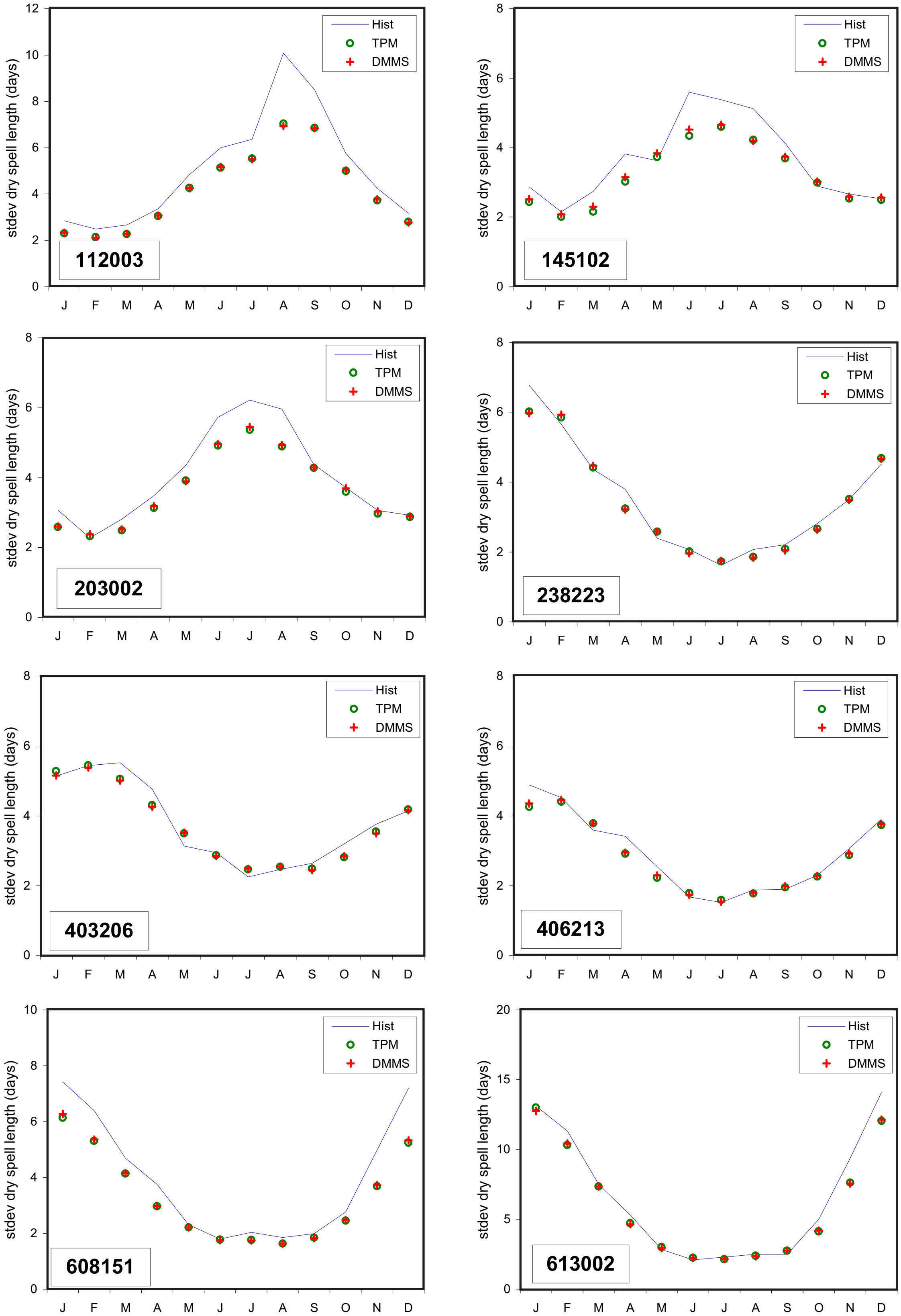


Figure B.2 Daily statistics for generated rainfall using TPM and DMMS models
(h) Standard deviation of dry spell length (days)

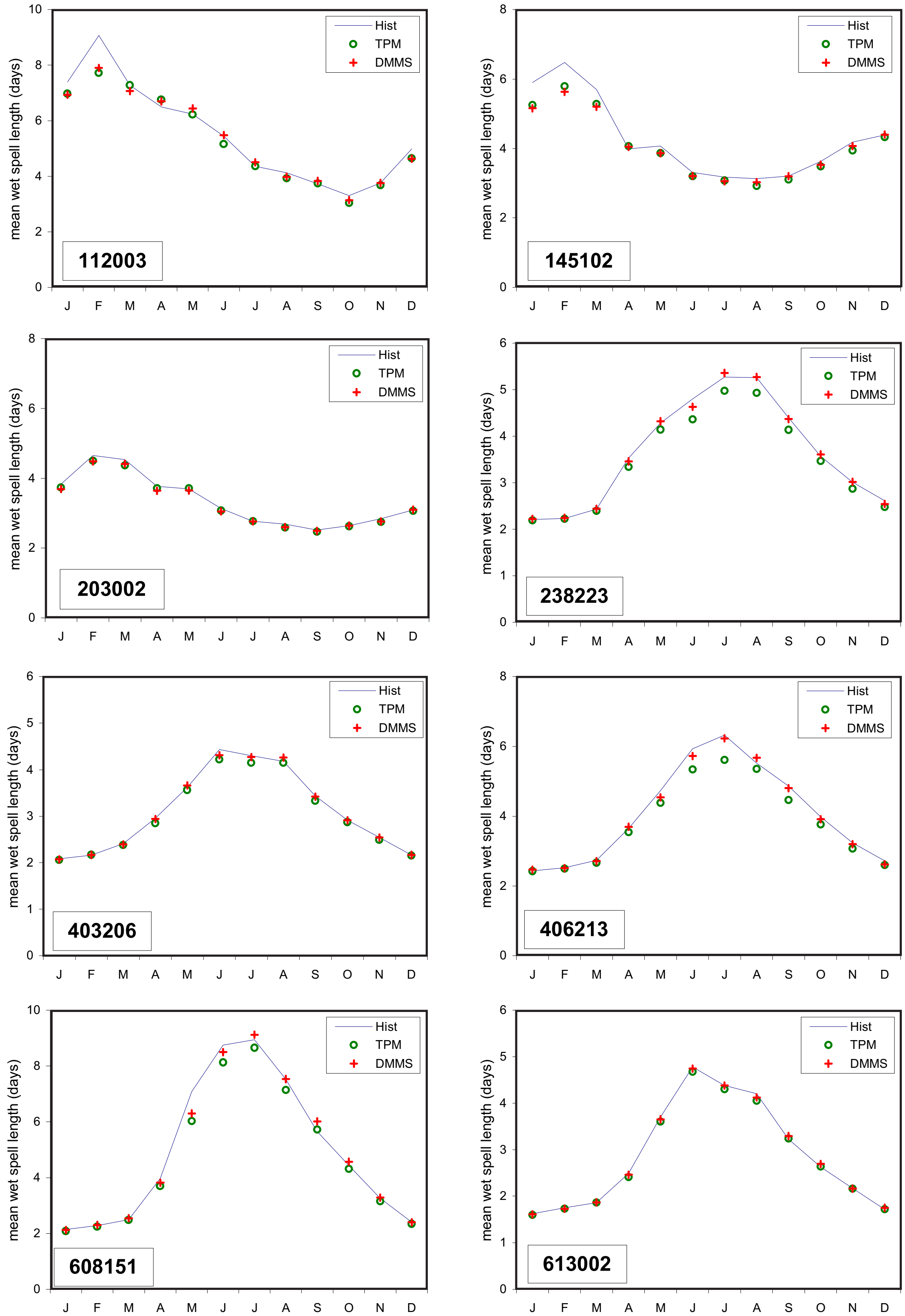


Figure B.2 Daily statistics for generated rainfall using TPM and DMMS models
(i) Mean wet spell length (days)

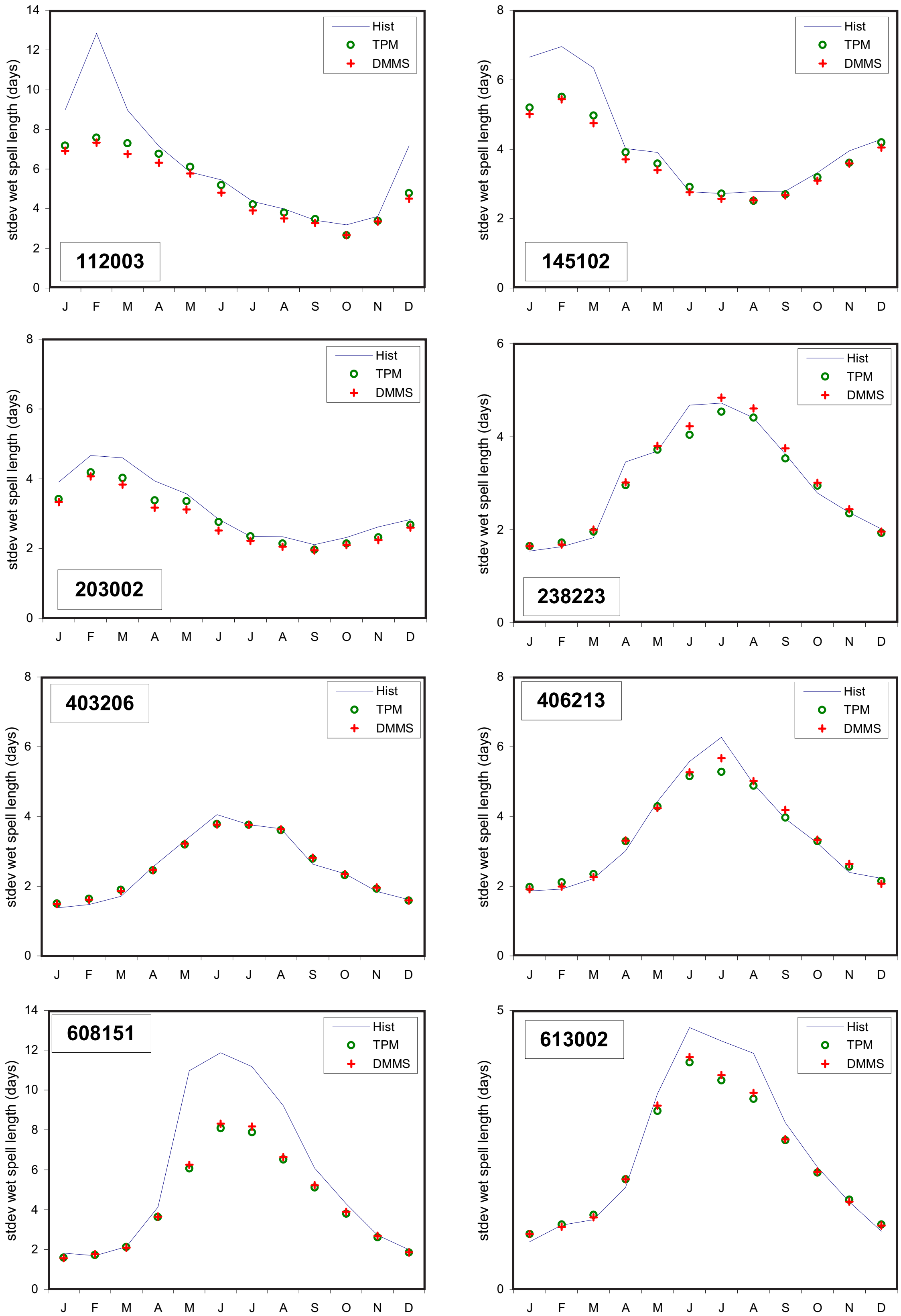


Figure B.2 Daily statistics for generated rainfall using TPM and DMMS models
(j) Standard deviation of wet spell length (days)

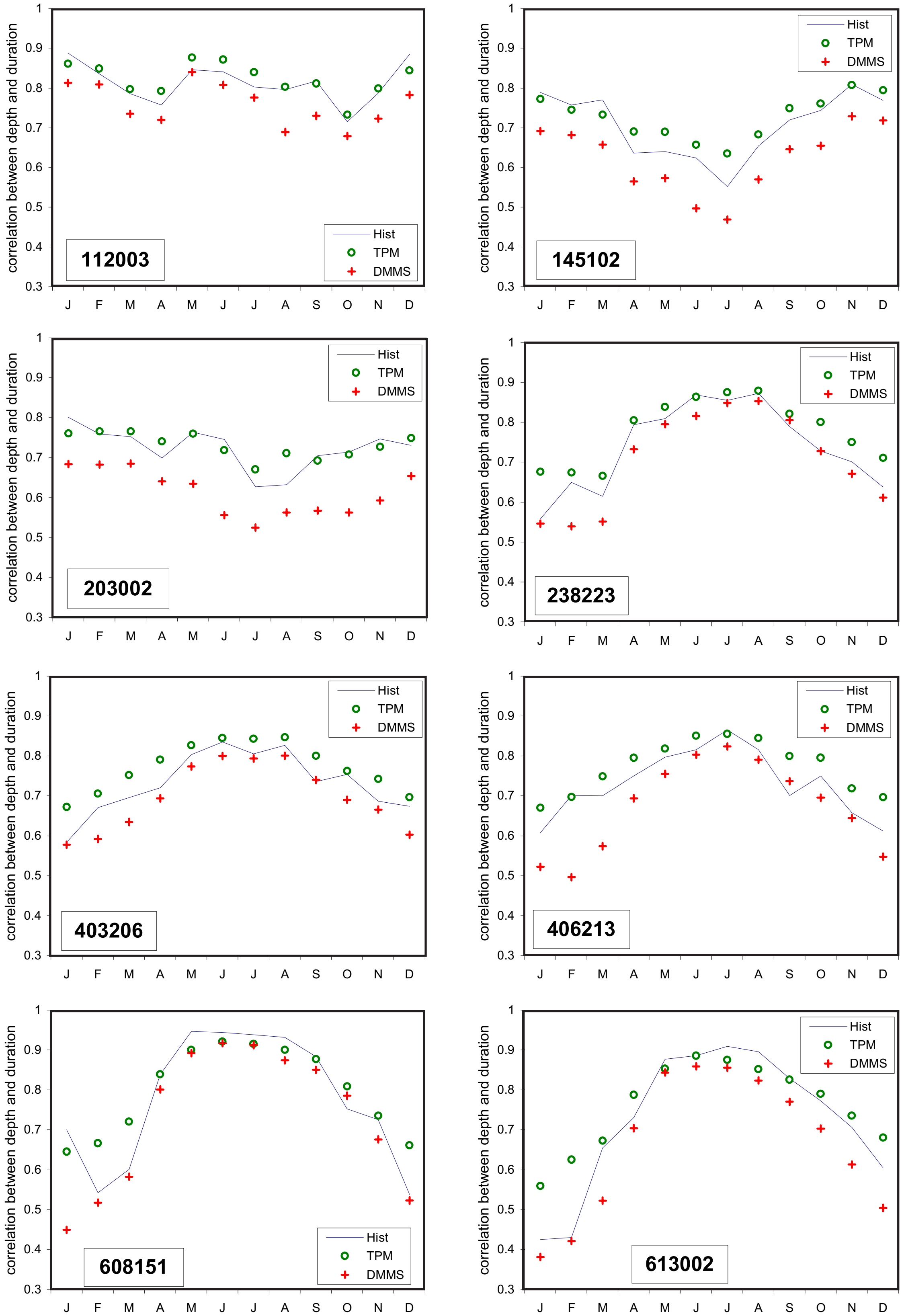


Figure B.2 Daily statistics for generated rainfall using TPM and DMMS models
(k) Correlation between rainfall depth and duration of wet spells

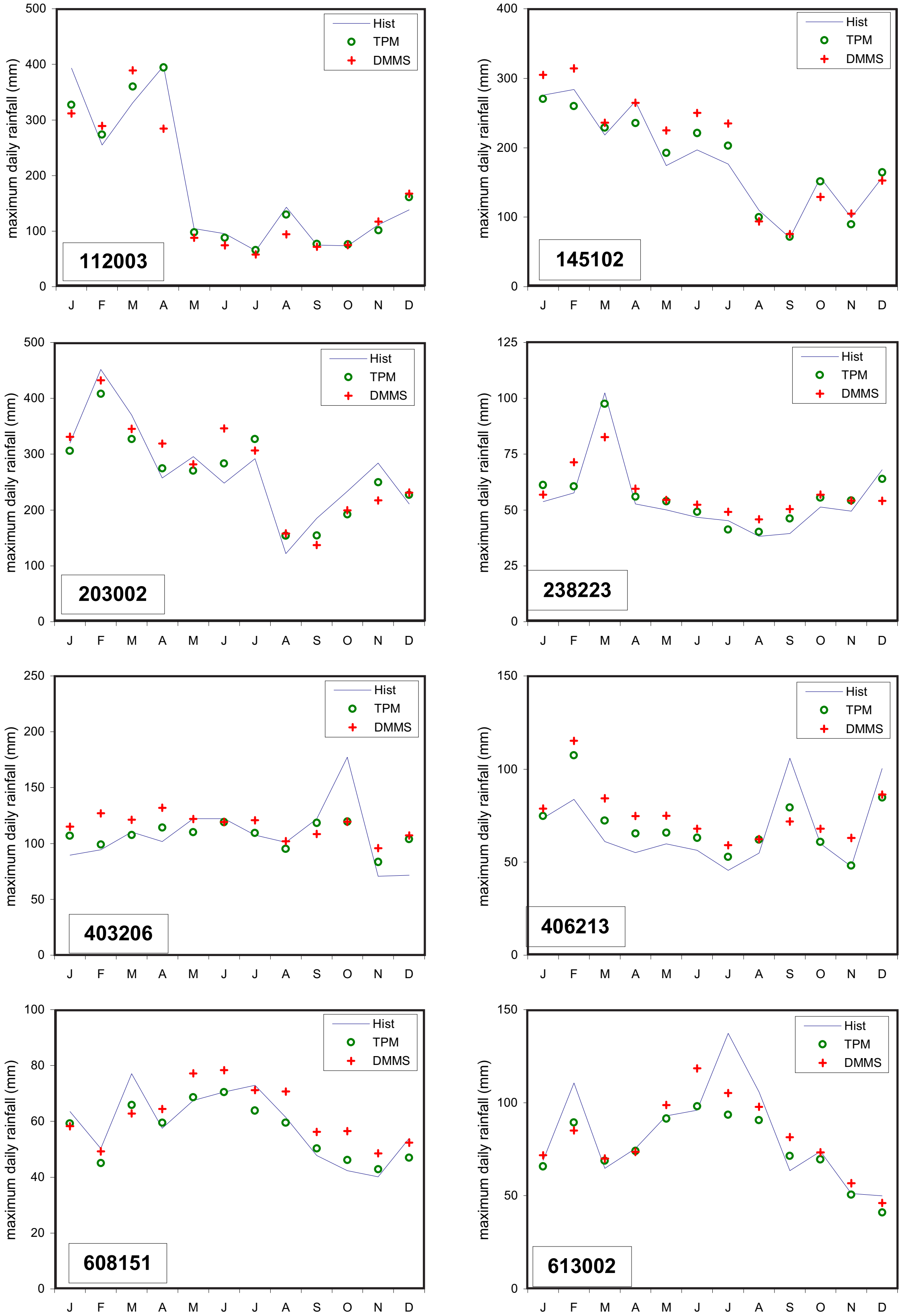


Figure B.2 Daily statistics for generated rainfall using TPM and DMMS models
(l) Maximum daily rainfall for each month

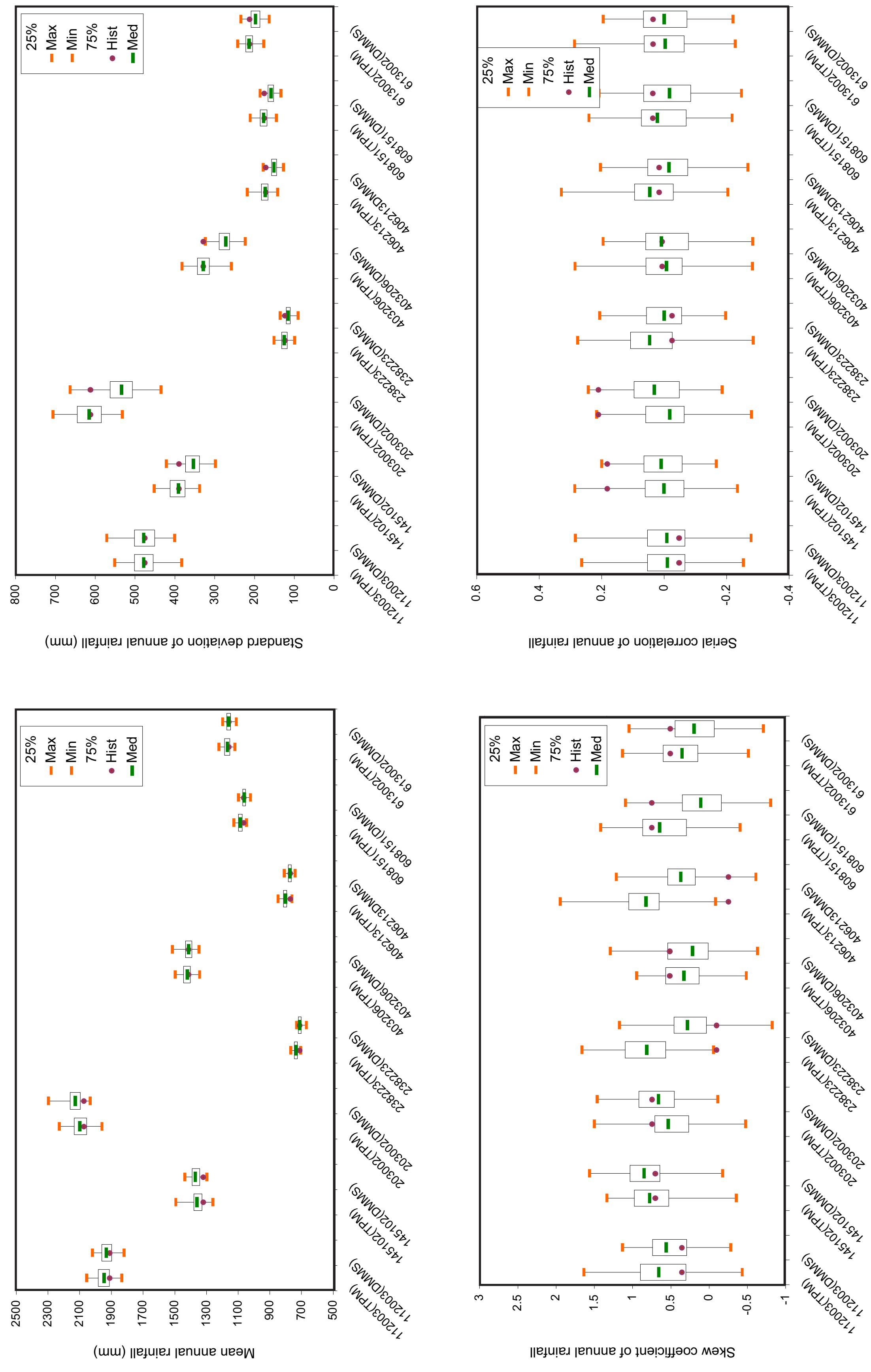


Figure B.3 Comparison of annual statistics for generated rainfall using TPM and DMMS models

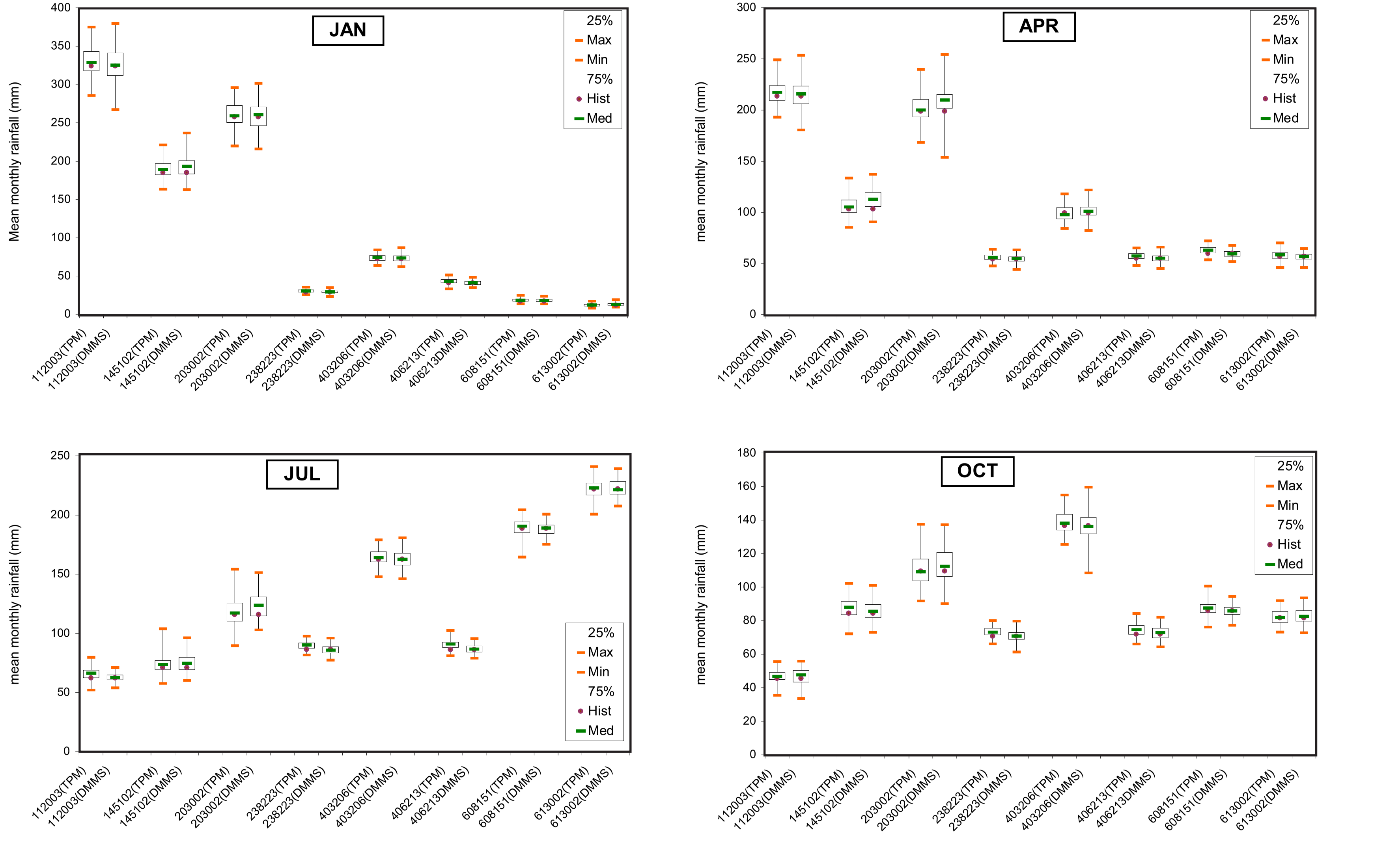


Figure B.4 Comparison of monthly statistics for generated rainfall using TPM and DMMS models
(a) Mean monthly rainfall

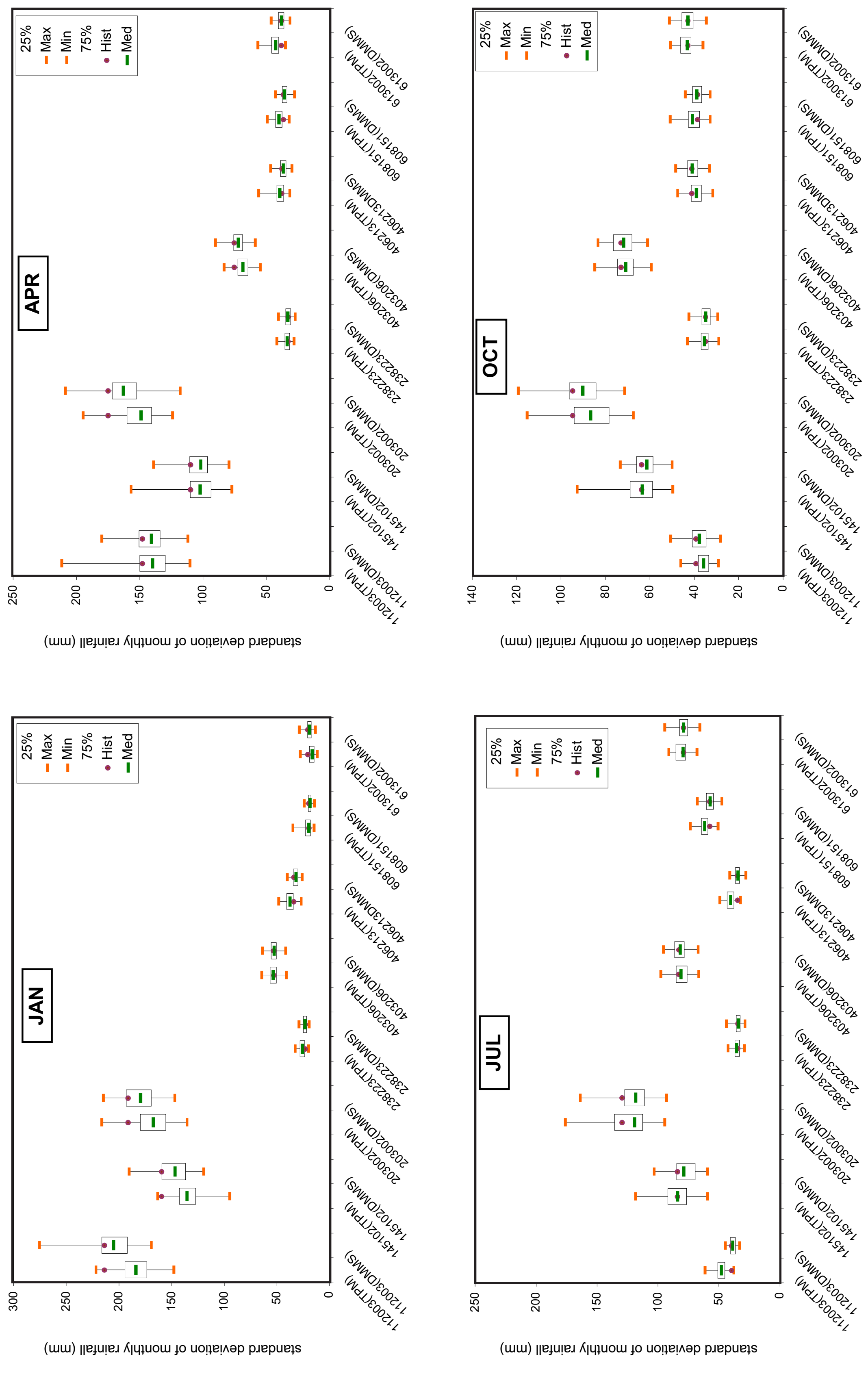


Figure B.4 Comparison of monthly statistics for generated rainfall using TPM and DMMS models
(b) Standard deviation of monthly rainfall

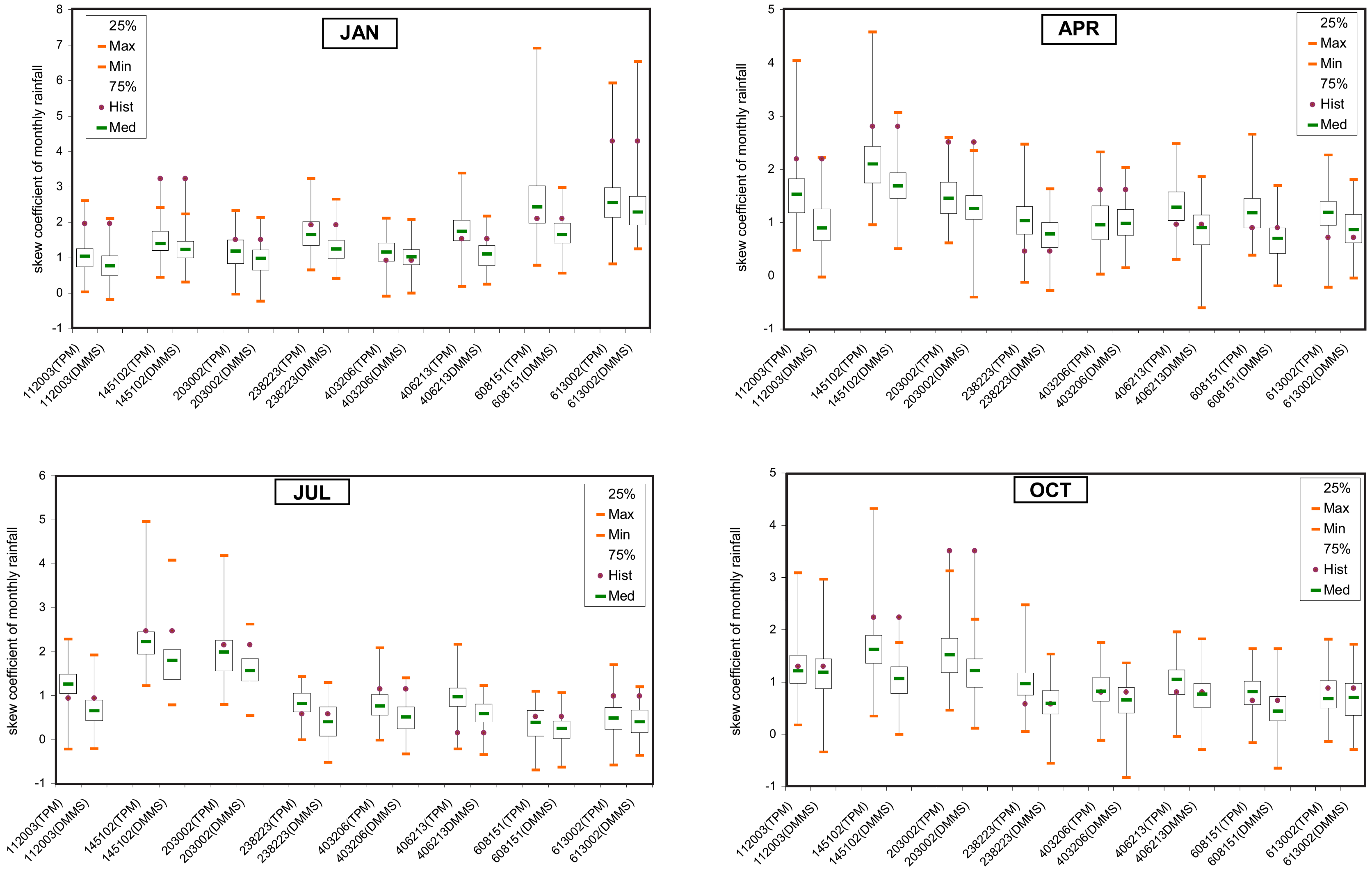


Figure B.4 Comparison of monthly statistics for generated rainfall using TPM and DMMS models
(c) Skew coefficient of monthly rainfall

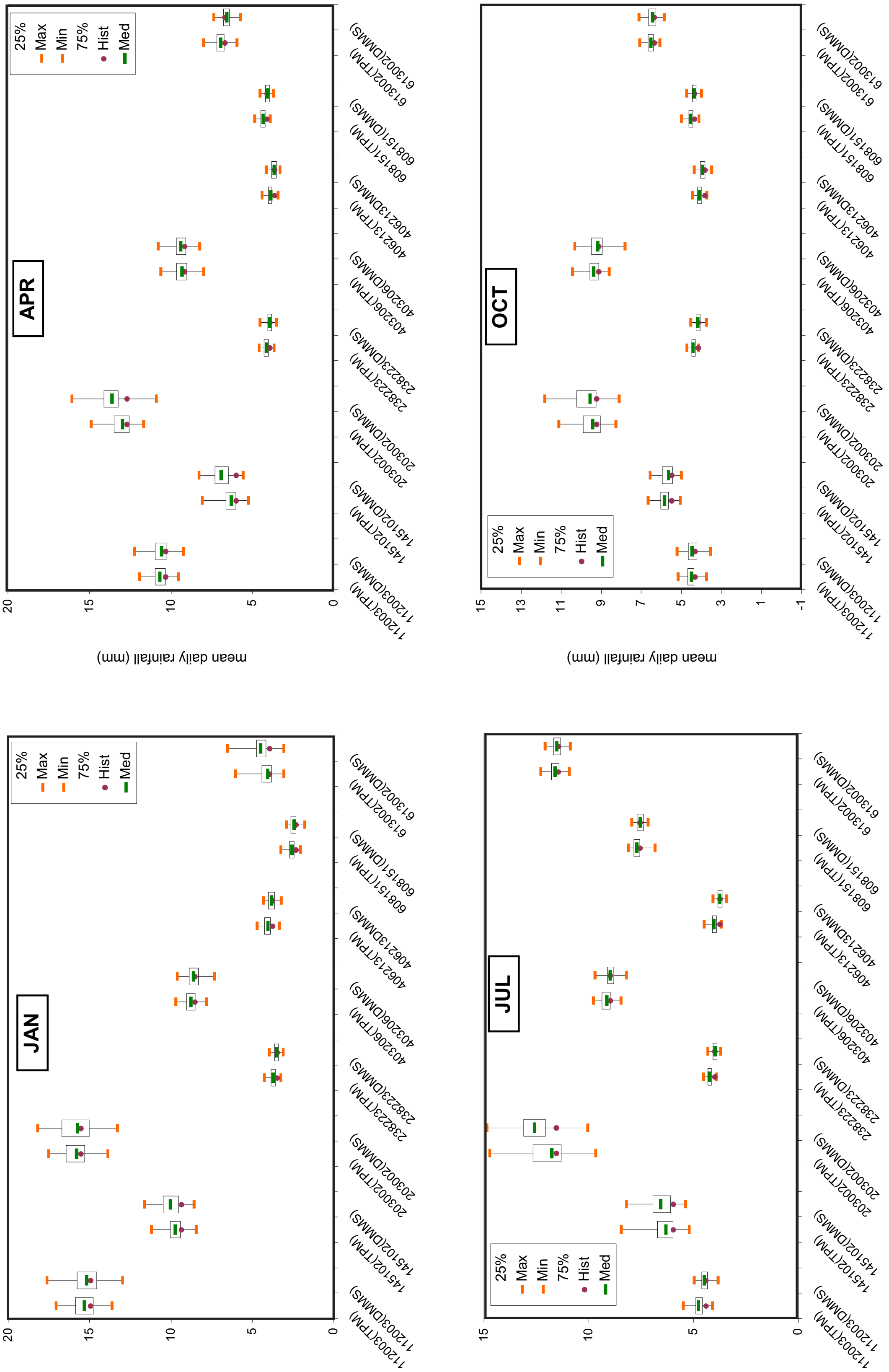


Figure B.5 Comparison of daily statistics for generated rainfall using TPM and DMMS models
(a) Mean daily rainfall

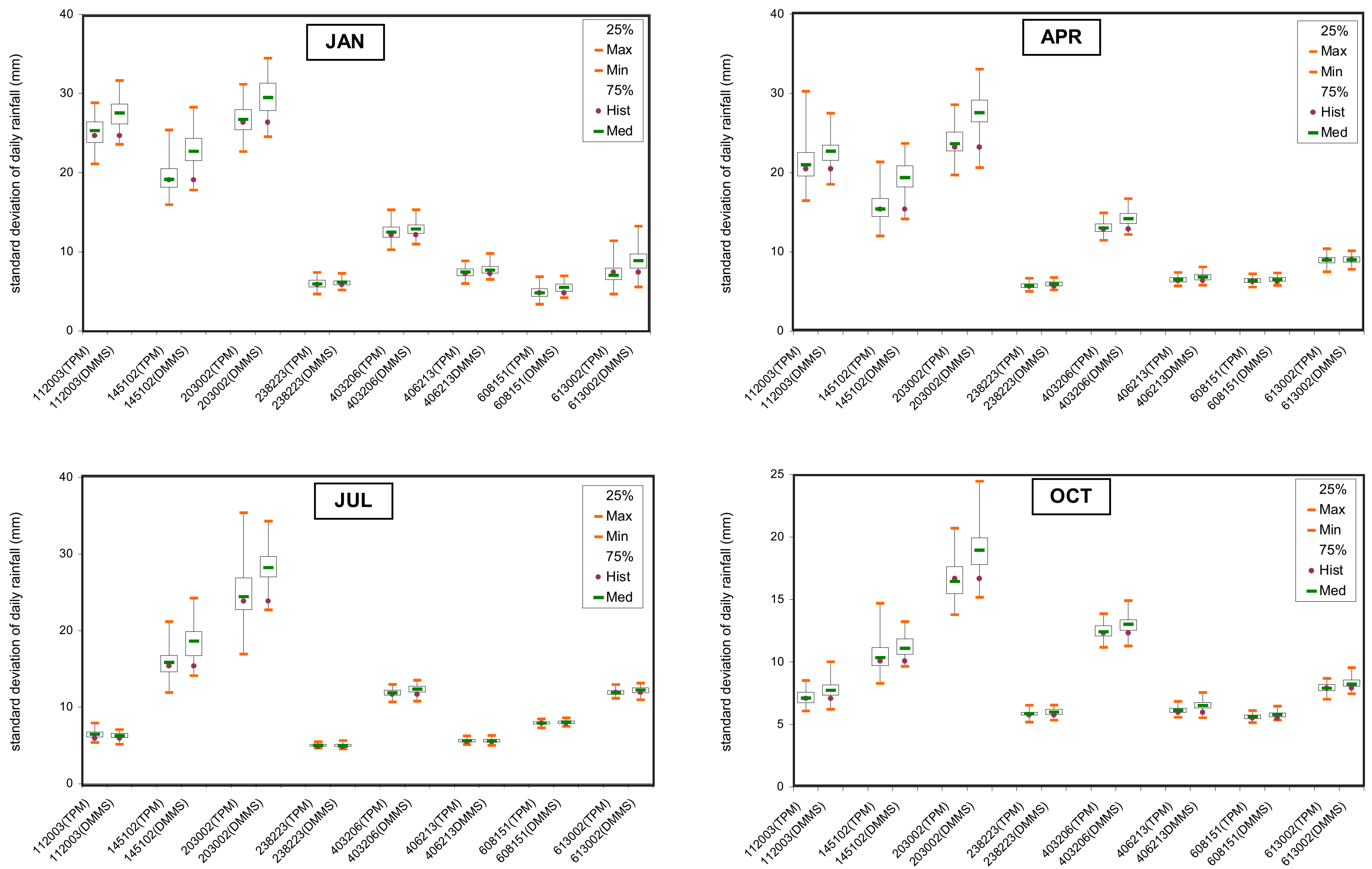


Figure B.5 Comparison of daily statistics for generated rainfall using TPM and DMMS models
(b) Standard deviation daily rainfall

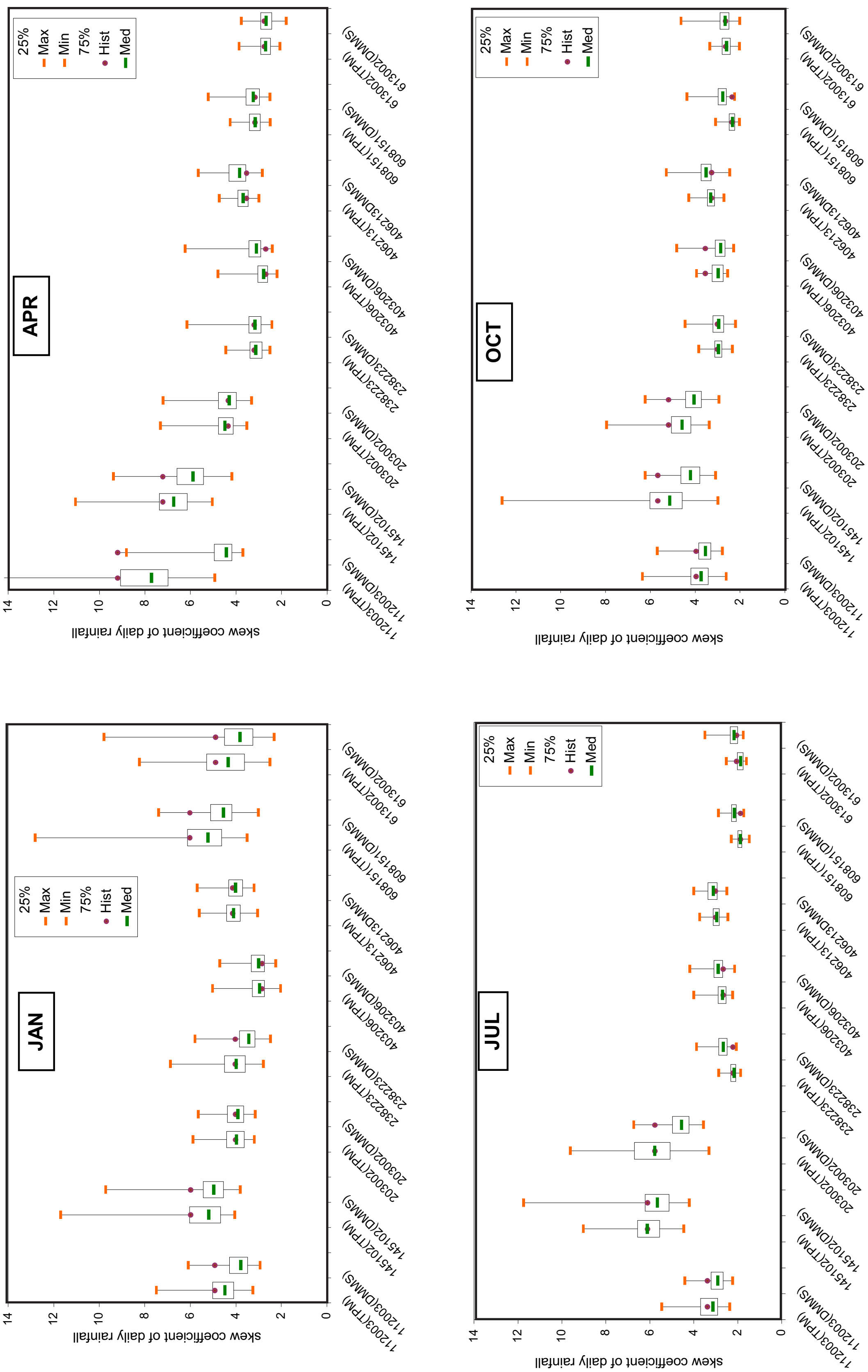


Figure B.5 : Comparison of daily statistics for generated rainfall using TPM and DMMS models

(c) Skew coefficient of daily rainfall

Appendix C: Comparison of Streamflow Statistics

Table C.1 Annual statistics for streamflow from generated rainfall using TPM and DMMS models

ANNUAL STATISTICS (mean values)

Catchment	Case	Annual (mm)	StdDev (mm)	Skew	R1	Min	Max	2-year Low	5-year Low	10-year Low
112003	Historical	926	409	0.69	-0.10	0.09	2.24	0.80	2.94	7.76
	TPM	939	388	0.72	0.02	0.24	2.31	0.80	3.11	7.47
	DMMS	907	391	0.47	0.00	0.20	2.30	0.72	2.88	7.18
145102	Historical	261	230	2.00	0.20	0.08	5.12	0.18	1.46	5.36
	TPM	270	212	1.62	0.04	0.08	4.28	0.35	1.82	5.54
	DMMS	296	204	1.72	0.05	0.12	4.05	0.49	2.43	6.71
203002	Historical	913	539	1.00	0.22	0.08	2.83	0.58	2.24	4.90
	TPM	909	521	0.65	0.00	0.07	2.75	0.42	2.27	6.32
	DMMS	956	467	0.86	0.02	0.14	2.61	0.64	2.78	7.25
238223	Historical	97	62	0.56	-0.10	0.07	2.53	0.35	2.23	5.85
	TPM	108	68	1.37	0.02	0.14	3.41	0.52	2.52	6.97
	DMMS	94	62	0.89	0.01	0.11	3.13	0.45	2.14	5.90
403206	Historical	423	250	1.19	0.07	0.17	3.07	0.56	2.98	6.33
	TPM	425	245	0.83	0.04	0.12	2.86	0.50	2.35	6.35
	DMMS	418	208	0.61	0.03	0.18	2.49	0.64	2.61	6.72
406213	Historical	134	91	0.61	-0.01	0.03	3.01	0.19	2.14	5.68
	TPM	146	102	1.31	0.02	0.07	3.60	0.38	2.18	6.31
	DMMS	127	86	0.72	0.01	0.08	3.07	0.37	1.99	5.72
608151	Historical	201	97	2.03	0.04	0.31	3.48	0.72	3.06	6.60
	TPM	207	90	1.32	0.04	0.26	2.70	0.85	3.14	7.60
	DMMS	193	80	0.72	0.04	0.25	2.46	0.80	2.97	7.08
613002	Historical	314	147	1.29	0.14	0.33	2.73	0.78	2.32	6.47
	TPM	314	140	0.96	0.04	0.25	2.50	0.80	2.98	7.26
	DMMS	305	131	0.71	0.05	0.26	2.38	0.83	2.94	7.06

Average values from 100 replicates

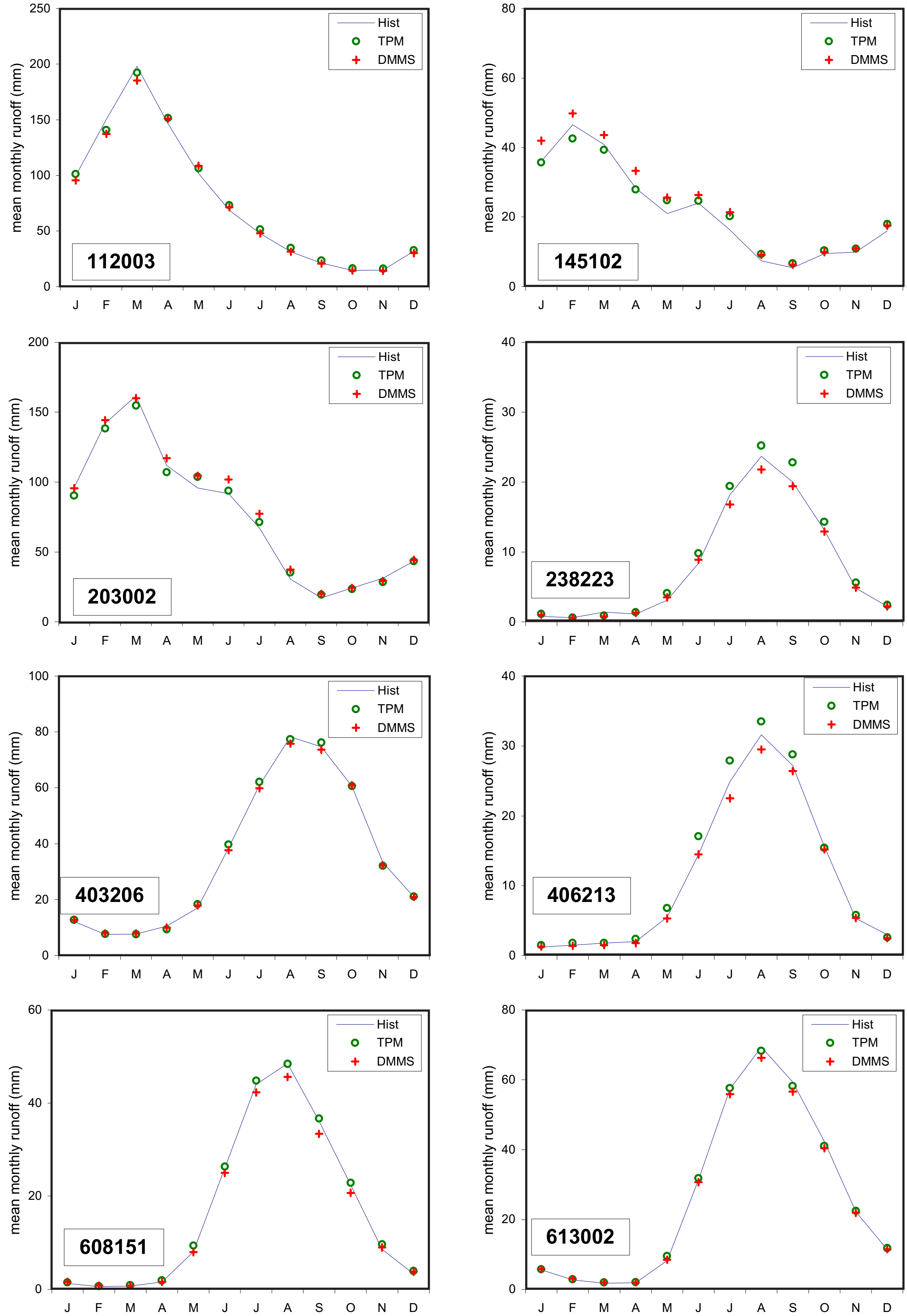


Figure C.1 Monthly statistics for streamflow modelled from generated rainfall using TPM and DMMS models
(a) Mean monthly runoff

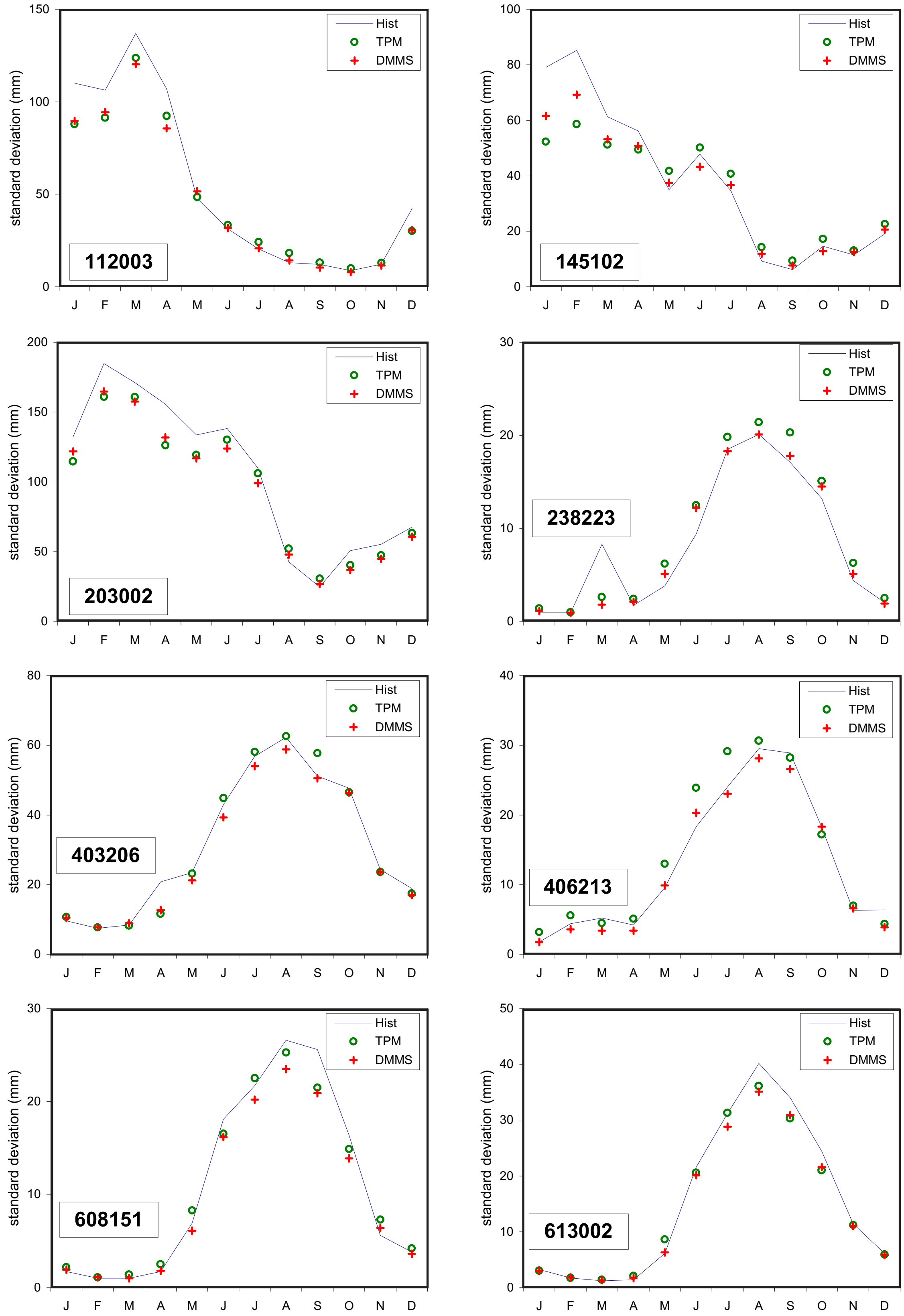


Figure C.1 Monthly statistics for streamflow modelled from generated rainfall using TPM and DMMS models (b) Standard deviation of monthly runoff

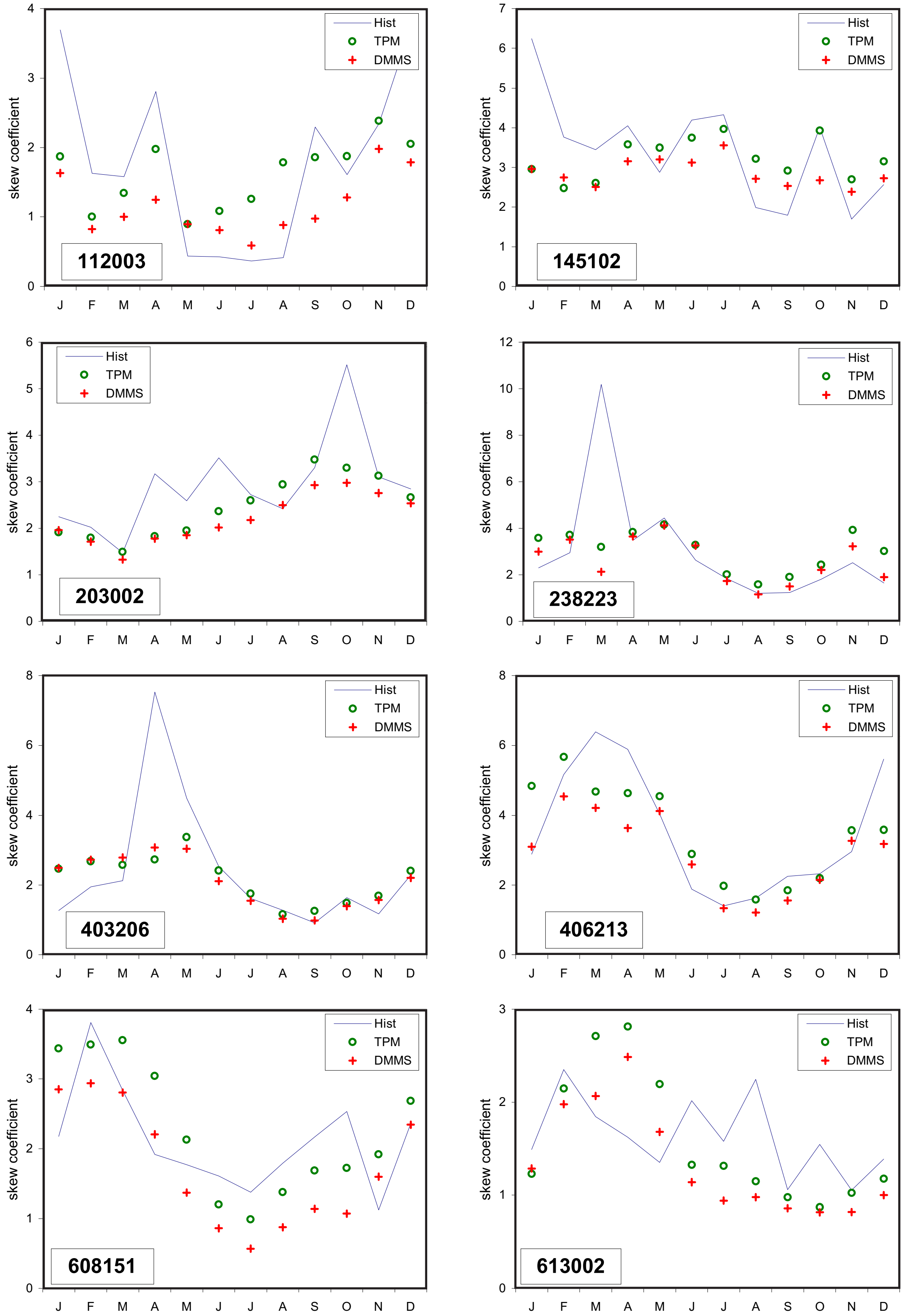


Figure C.1 Monthly statistics for streamflow modelled from generated rainfall using TPM and DMMS models
(c) Skew coefficient of monthly runoff

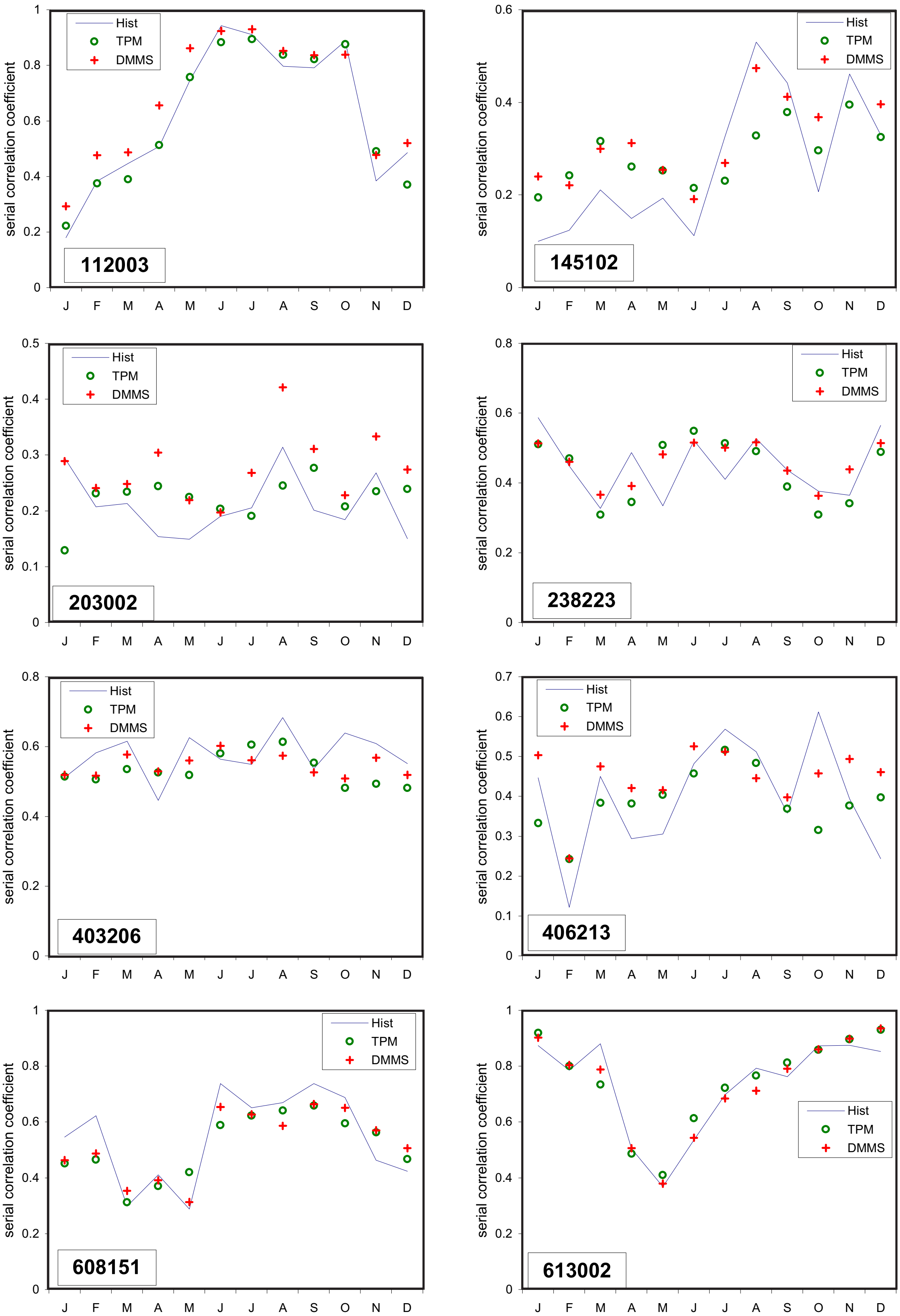


Figure C.1 Monthly statistics for streamflow modelled from generated rainfall using TPM and DMMS models (d) Serial correlation of monthly runoff

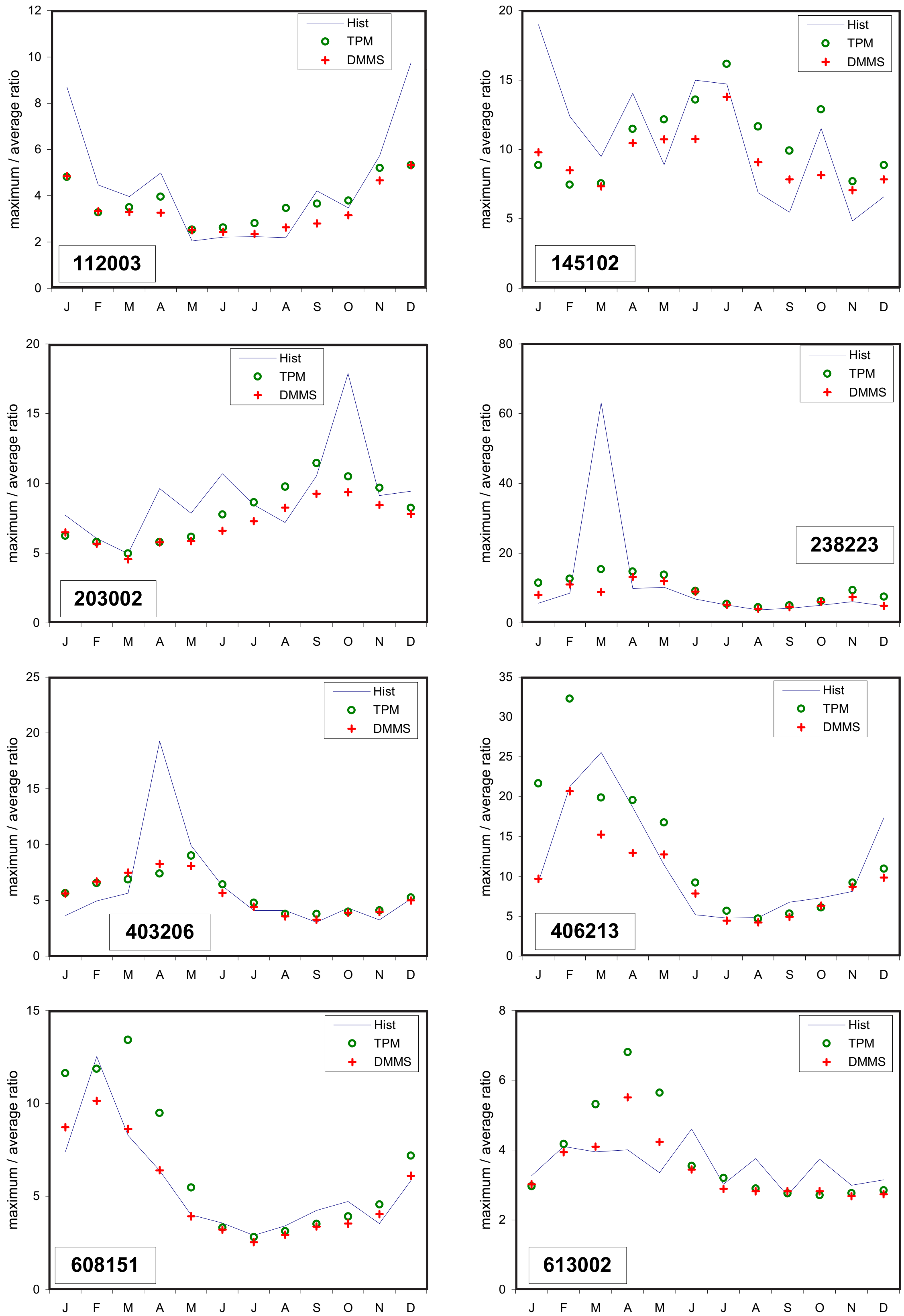


Figure C.1 Monthly statistics for streamflow modelled from generated rainfall using TPM and DMMS models (e) Maximum monthly runoff (standardised by mean)

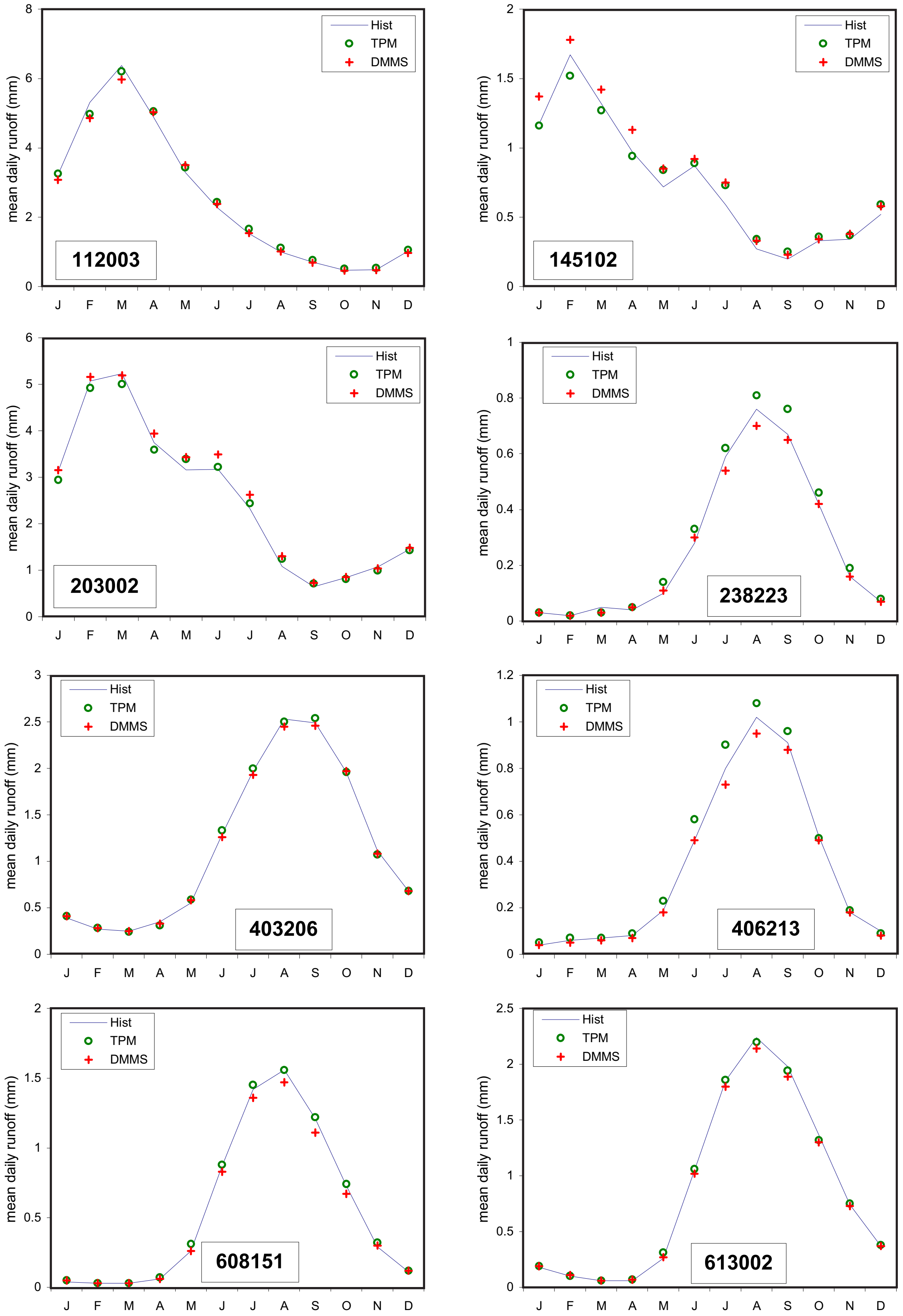


Figure C.2 Daily statistics for streamflow modelled from generated rainfall using TPM and DMMS models (a) Mean daily runoff

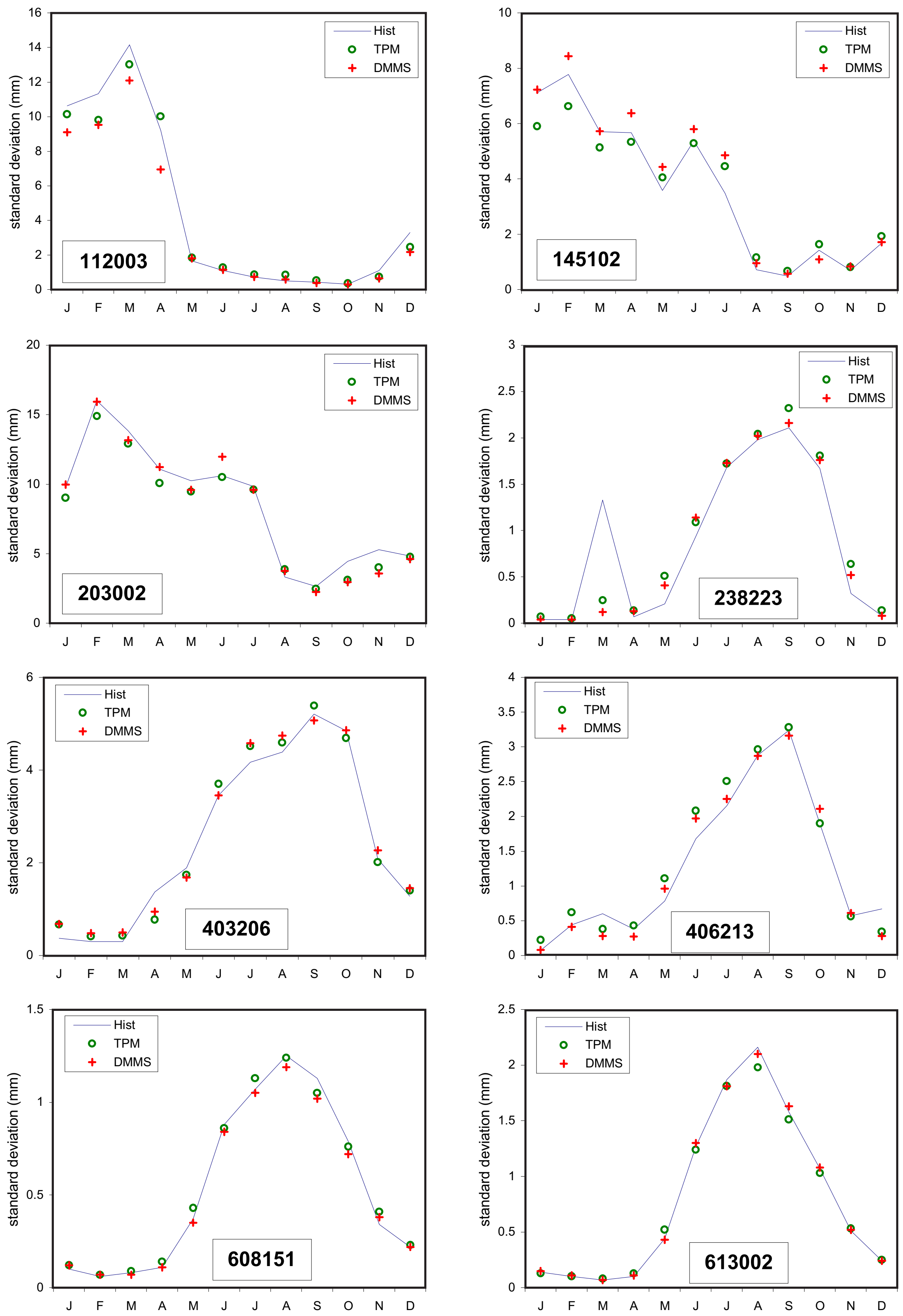


Figure C.2 Daily statistics for streamflow modelled from generated rainfall using TPM and DMMS models (b) Standard deviation of daily runoff

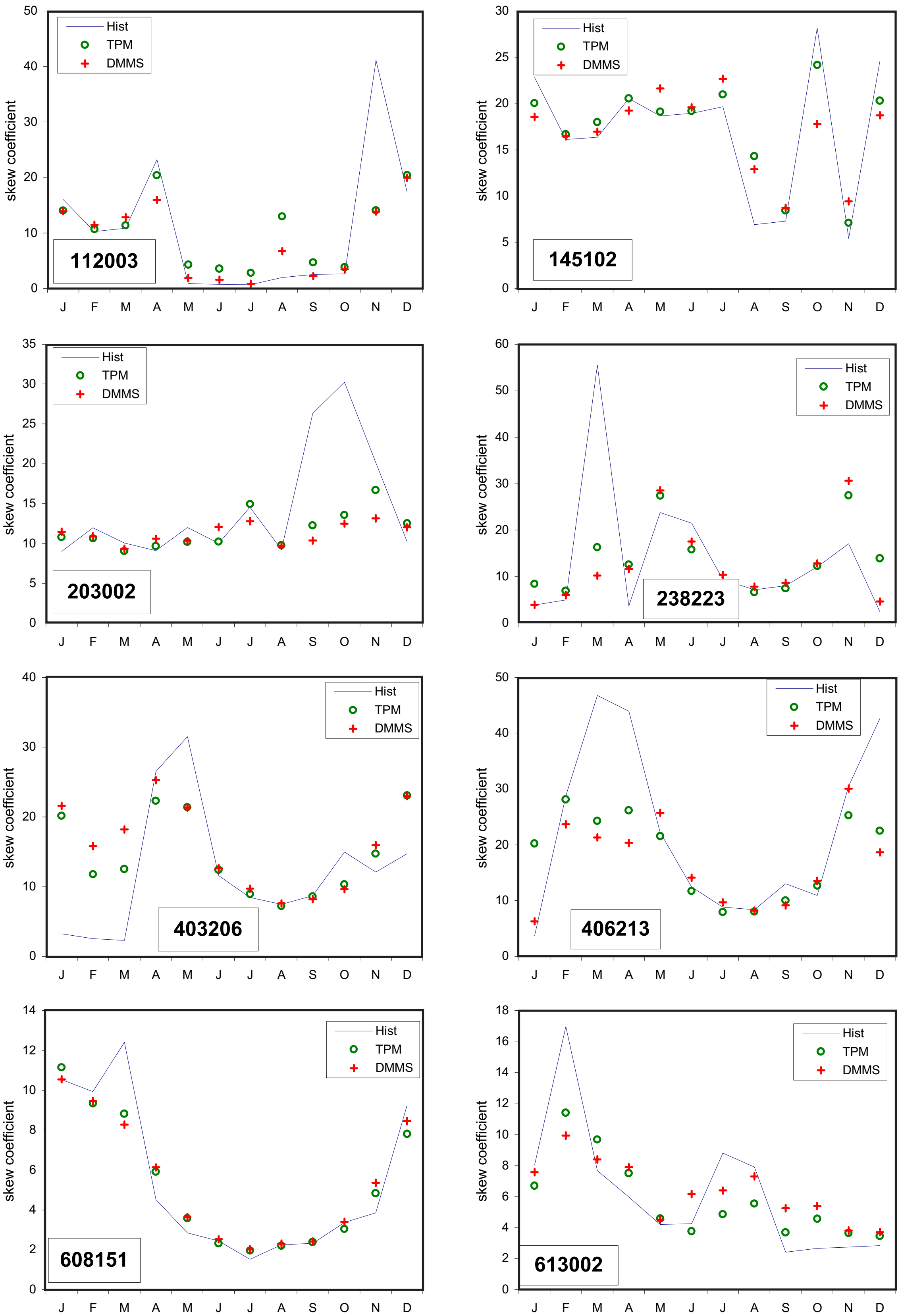


Figure C.2 Daily statistics for streamflow modelled from generated rainfall using TPM and DMMS models
(c) Skew coefficient of daily runoff

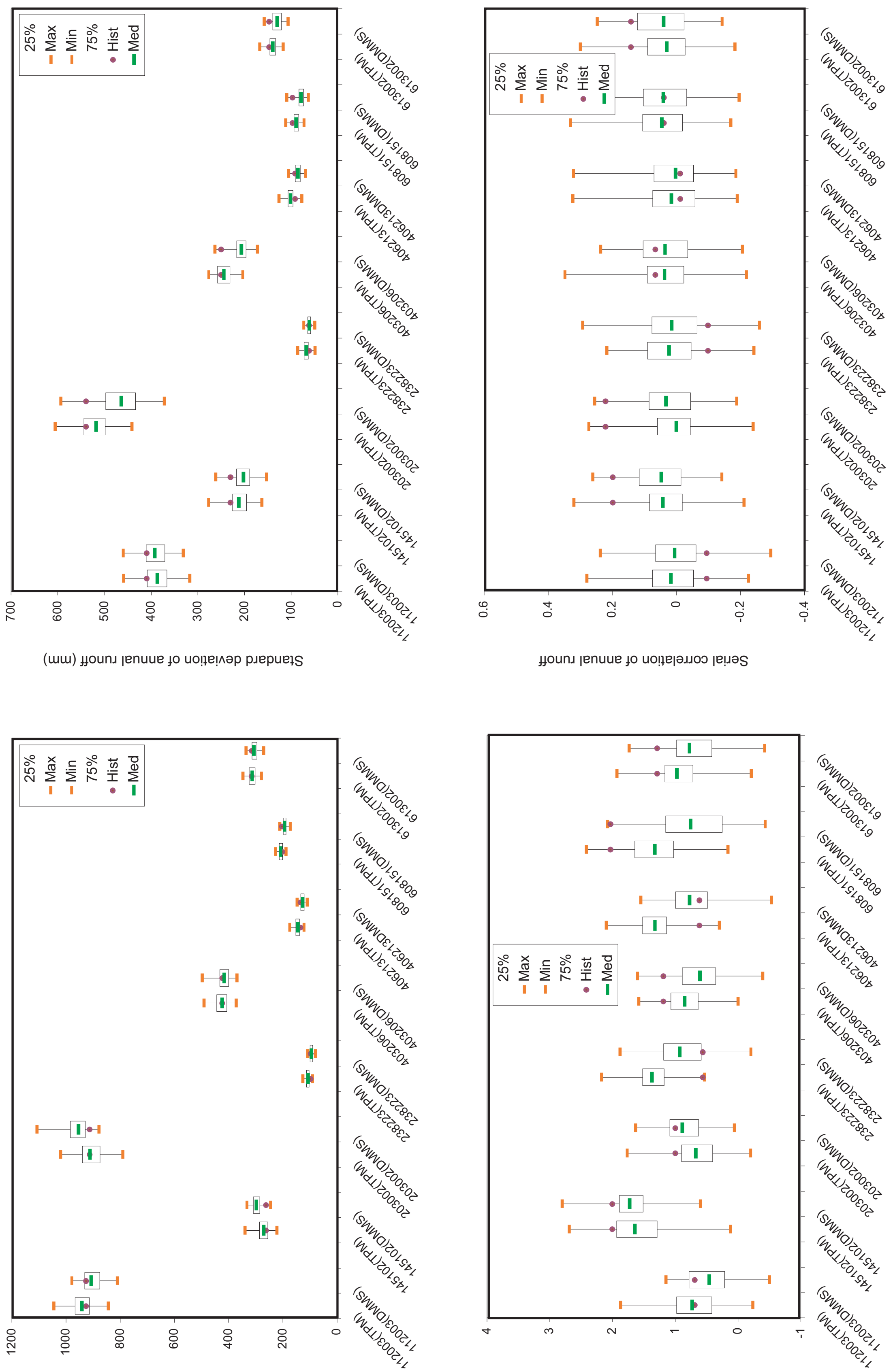


Figure C.3 Comparison of annual statistics for modelled streamflow using generated rainfall from TPM and DMMS models

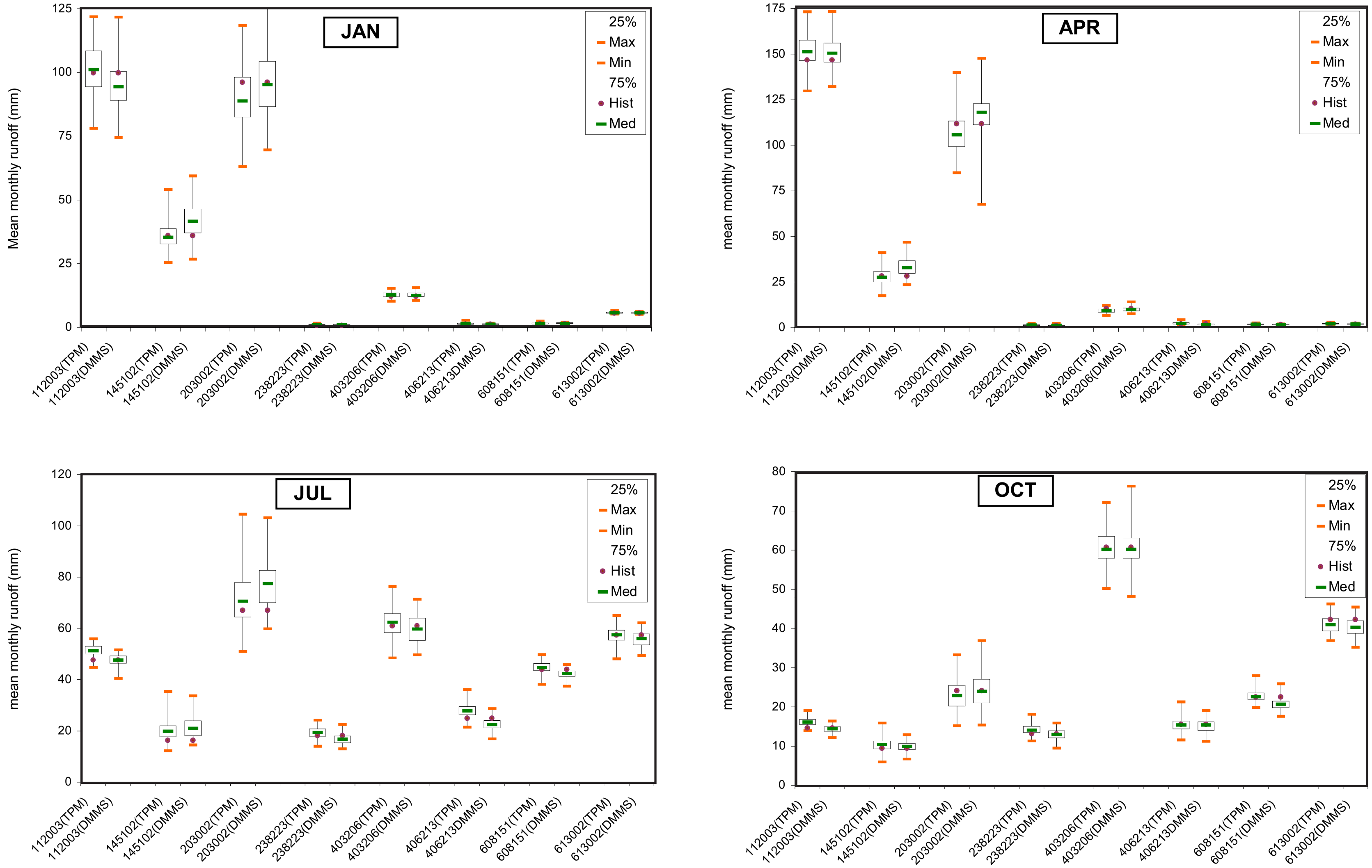


Figure C.4 Comparison of monthly statistics for modelled streamflow from generated rainfall using TPM and DMMS models
(a) Mean monthly runoff

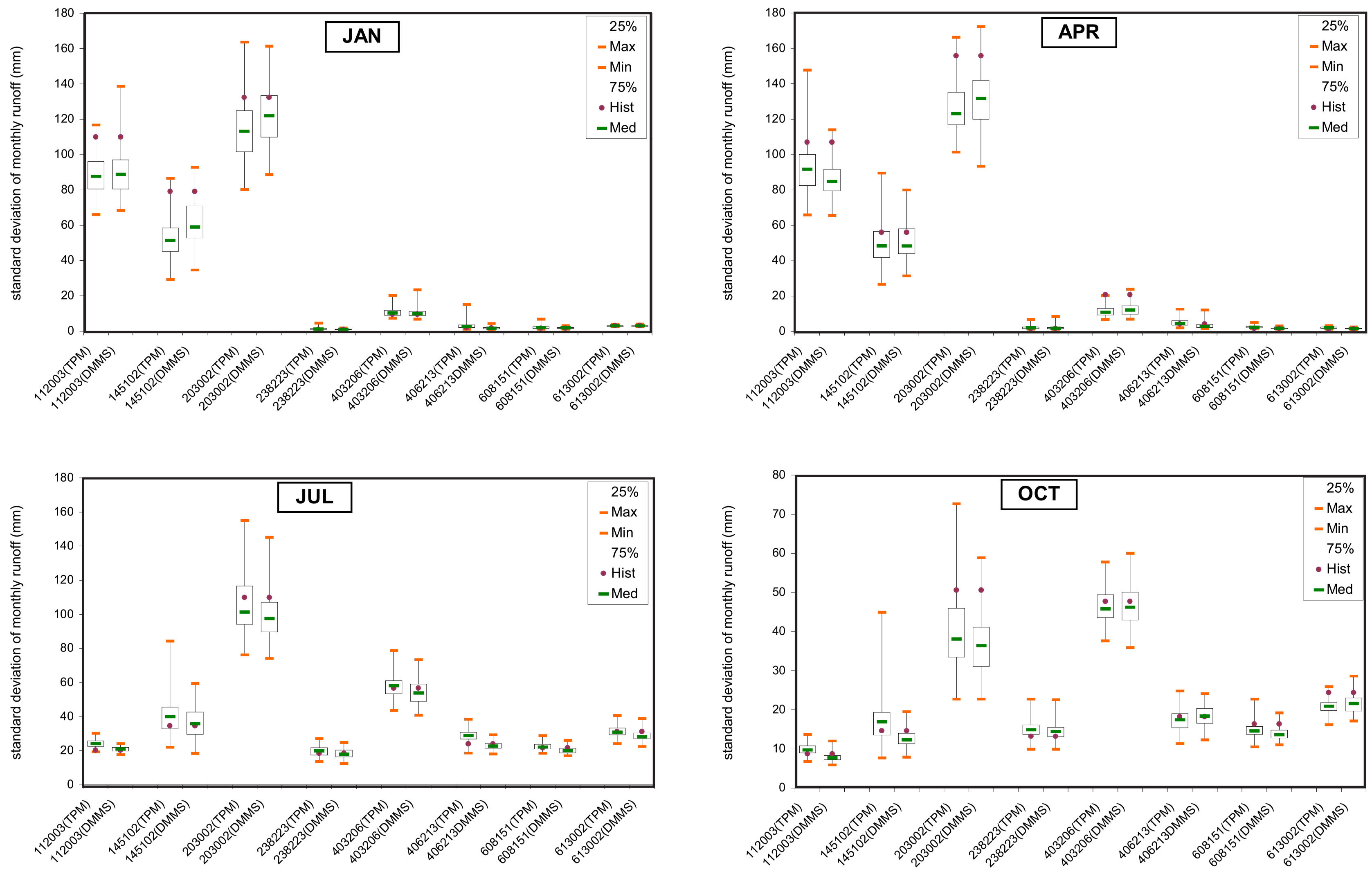


Figure C.4 Comparison of monthly statistics for modelled streamflow from generated rainfall using TPM and DMMS models
(b) Standard deviation of monthly runoff

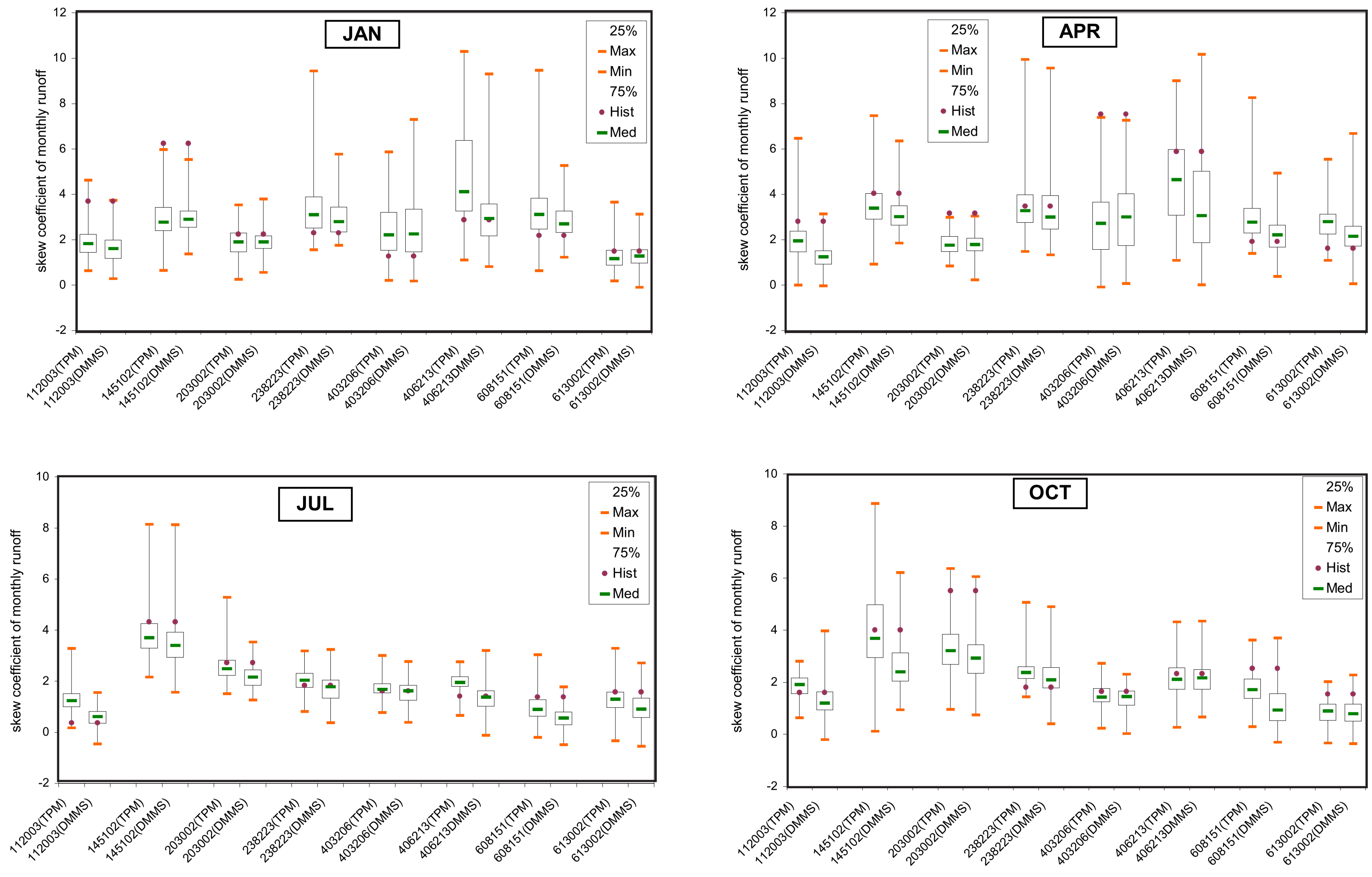


Figure C.4 Comparison of monthly statistics for modelled streamflow from generated rainfall using TPM and DMMS models
(c) Skew coefficient of monthly runoff

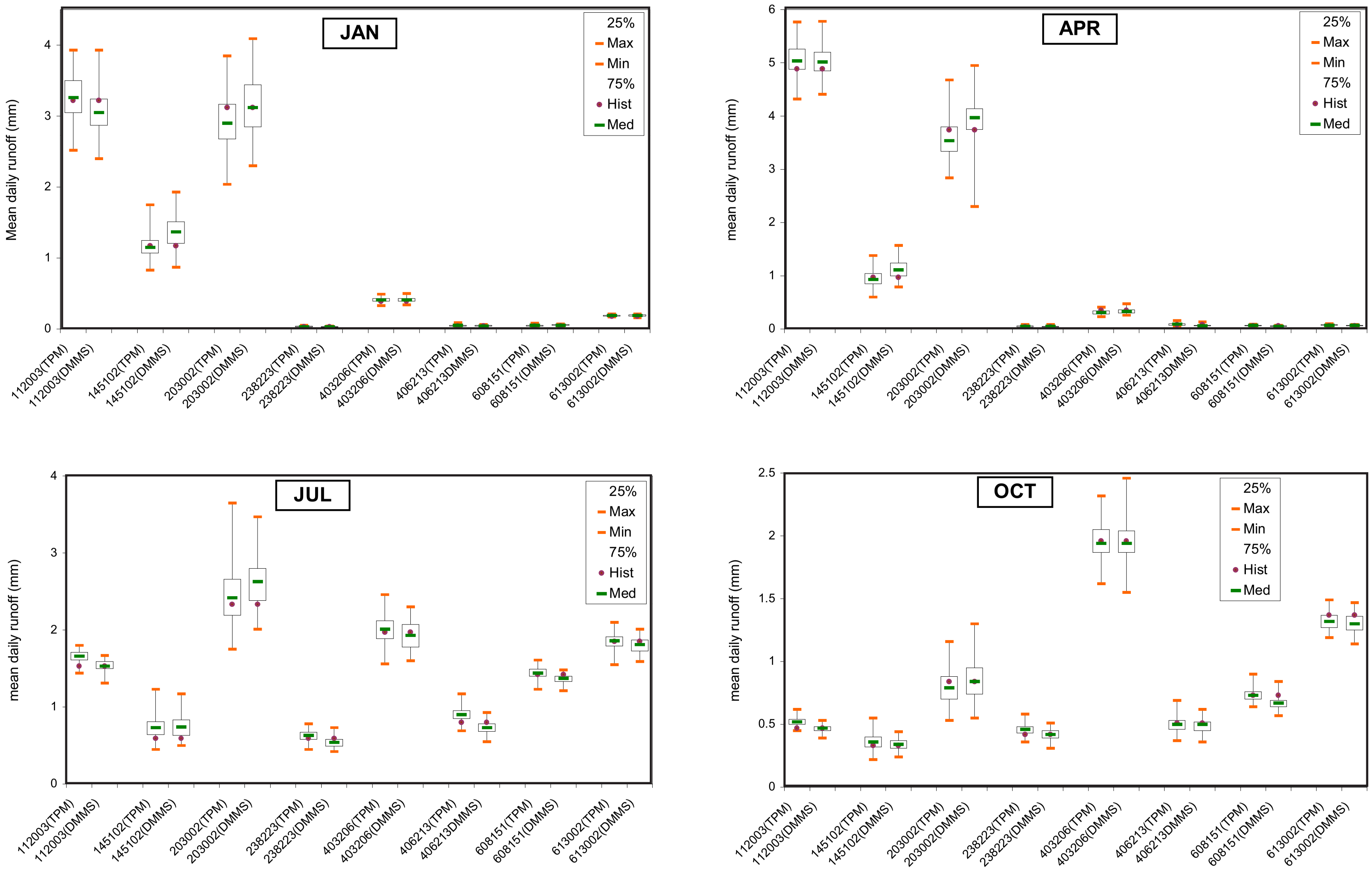


Figure C.5 Comparison of daily statistics for modelled streamflow from generated rainfall using TPM and DMMS models
(a) Mean daily runoff

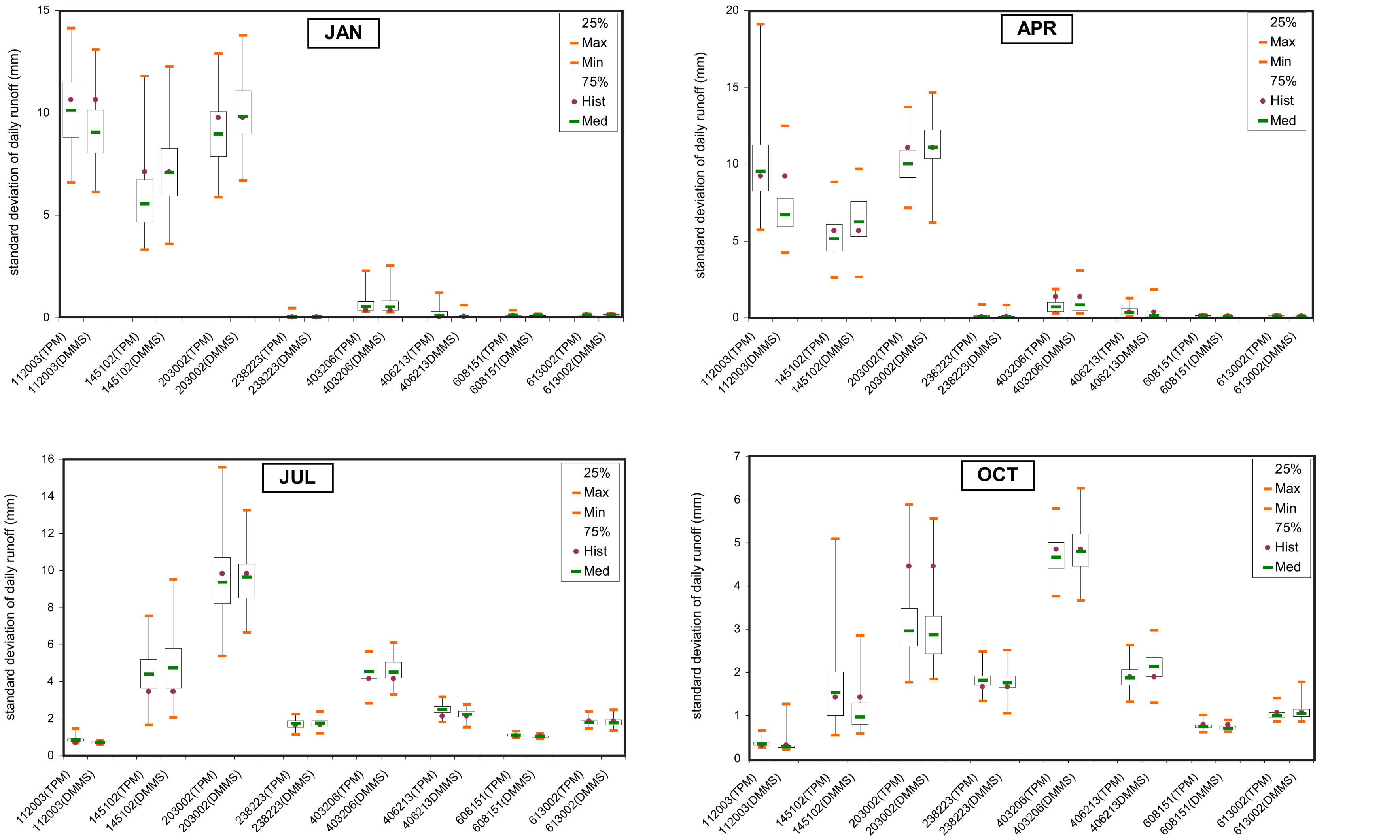


Figure C.5 Comparison of daily statistics for modelled streamflow from generated rainfall using TPM and DMMS models
(b) Standard deviation of daily runoff

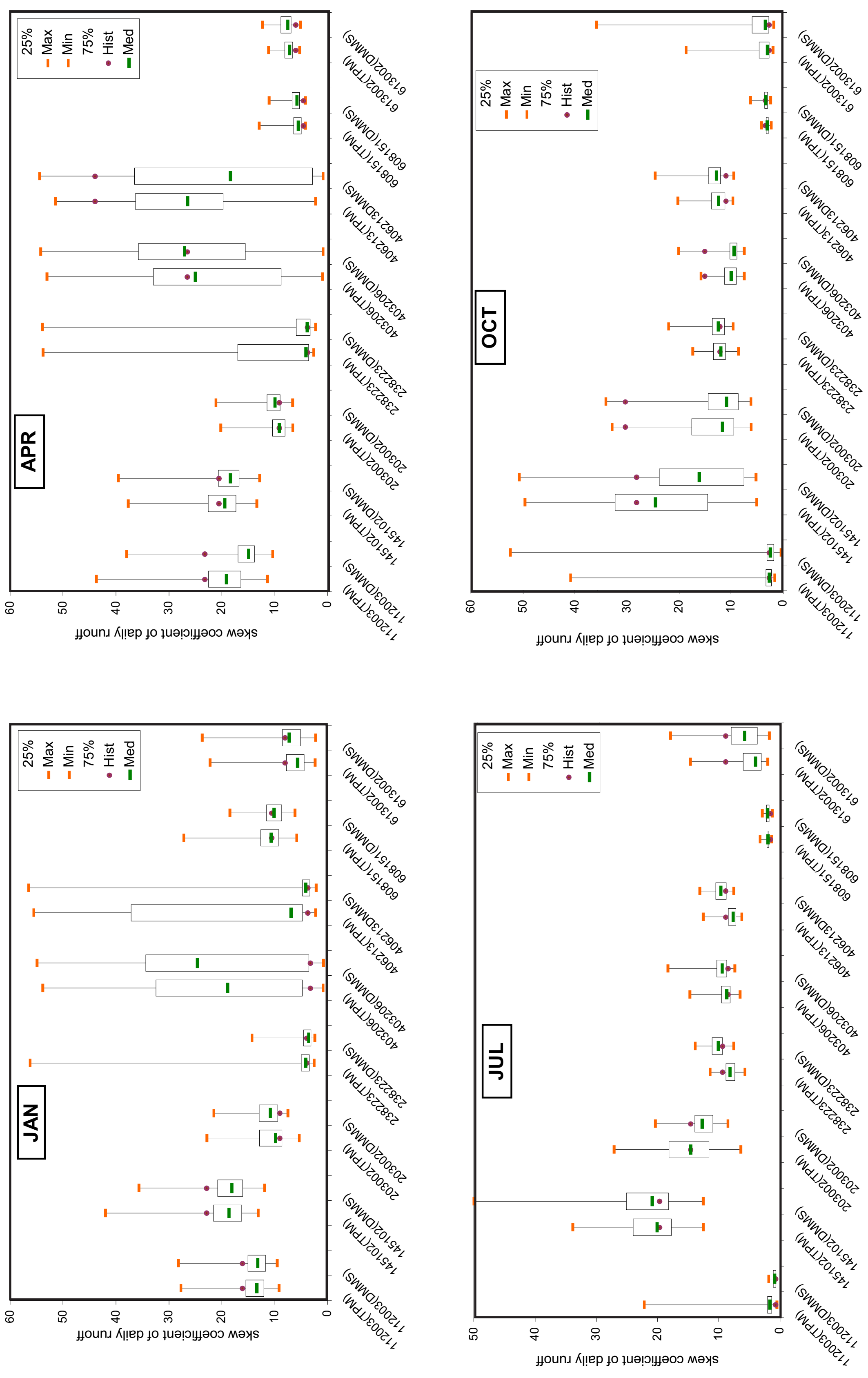


Figure C.5 Comparison of daily statistics for modelled streamflow from generated rainfall using TPM and DMMS models
(c) Skew coefficient of daily runoff

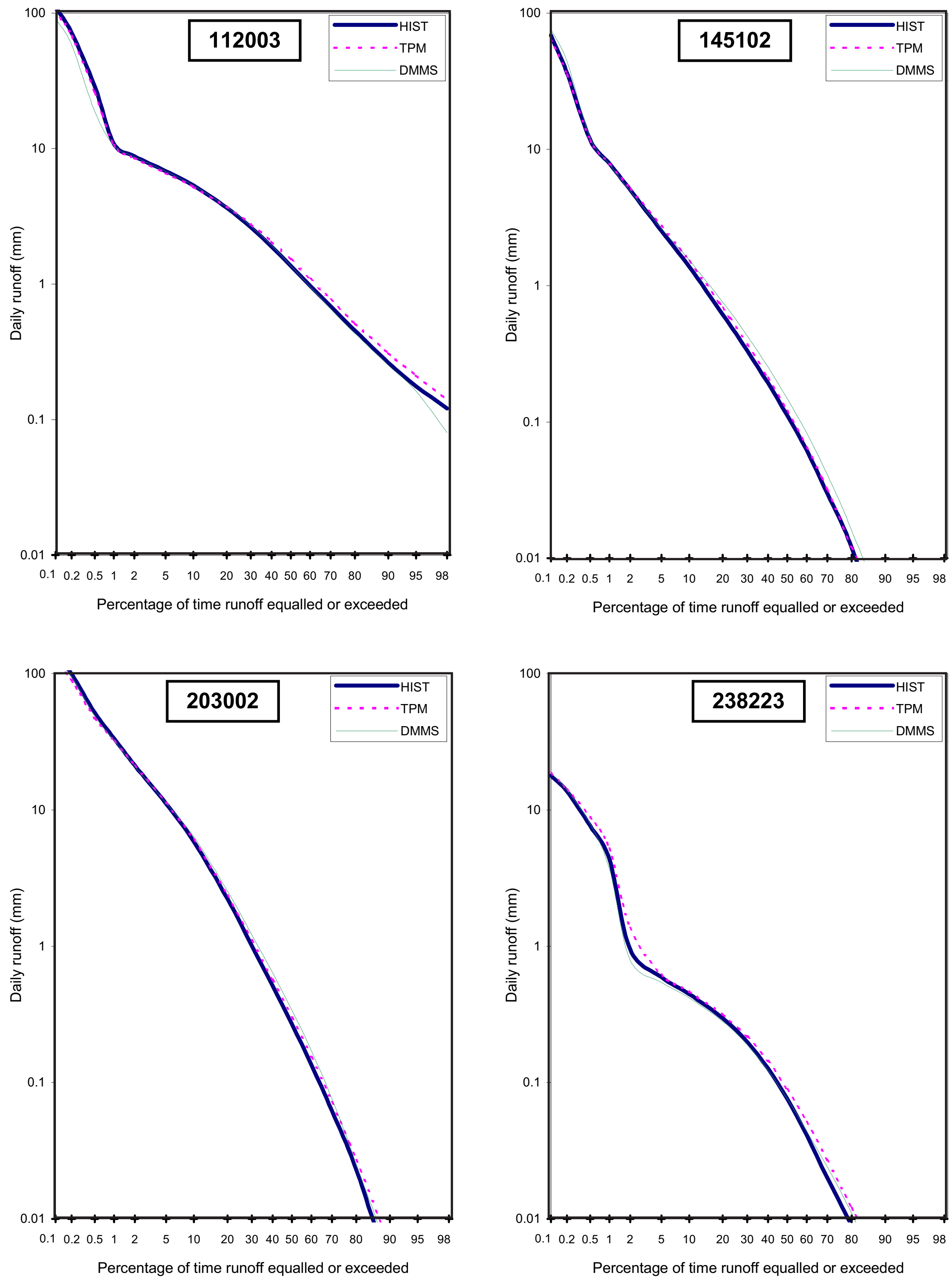


Figure C.6 Comparison of flow duration curves derived by modelling generated rainfall and historical rainfall

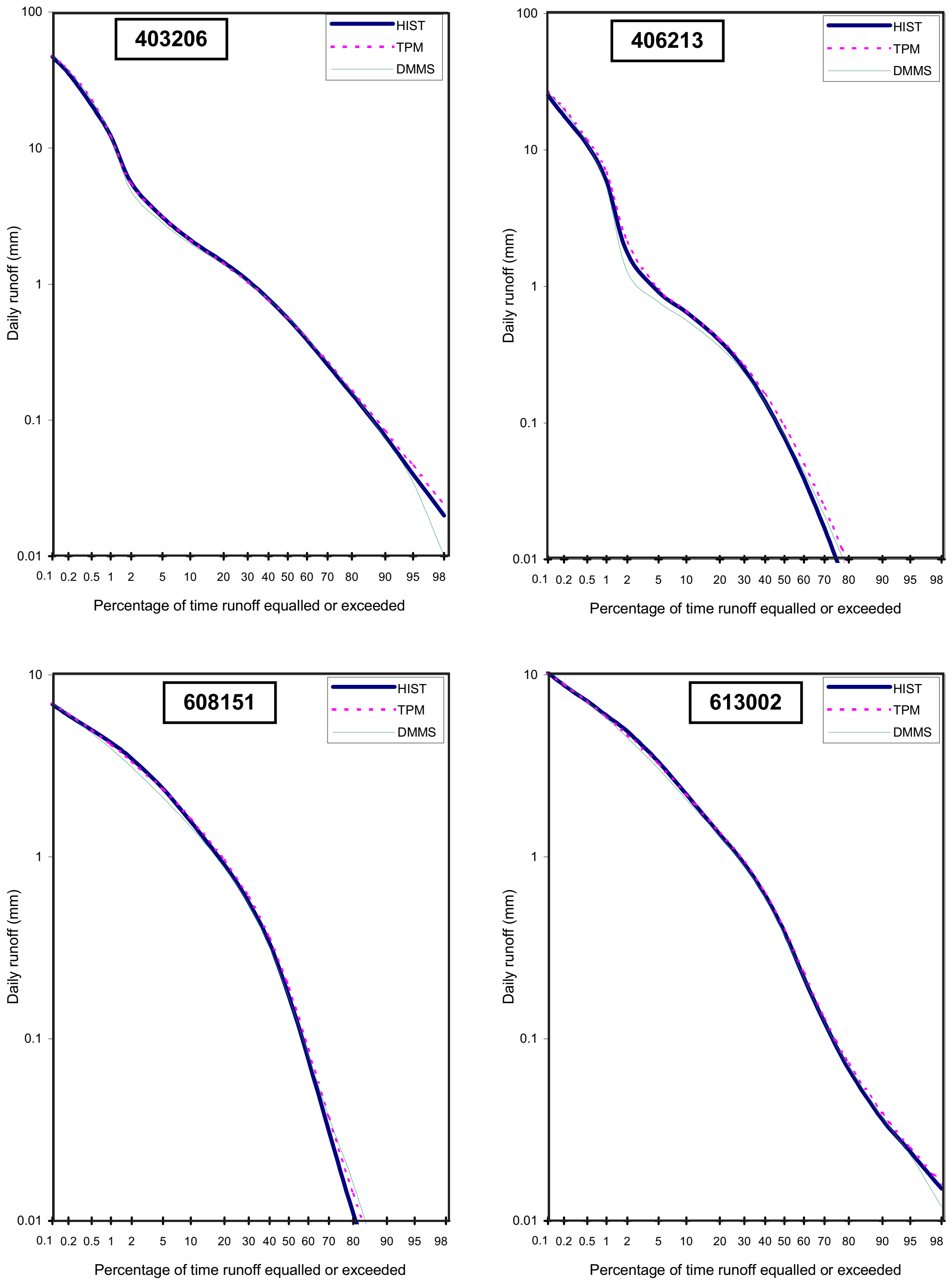
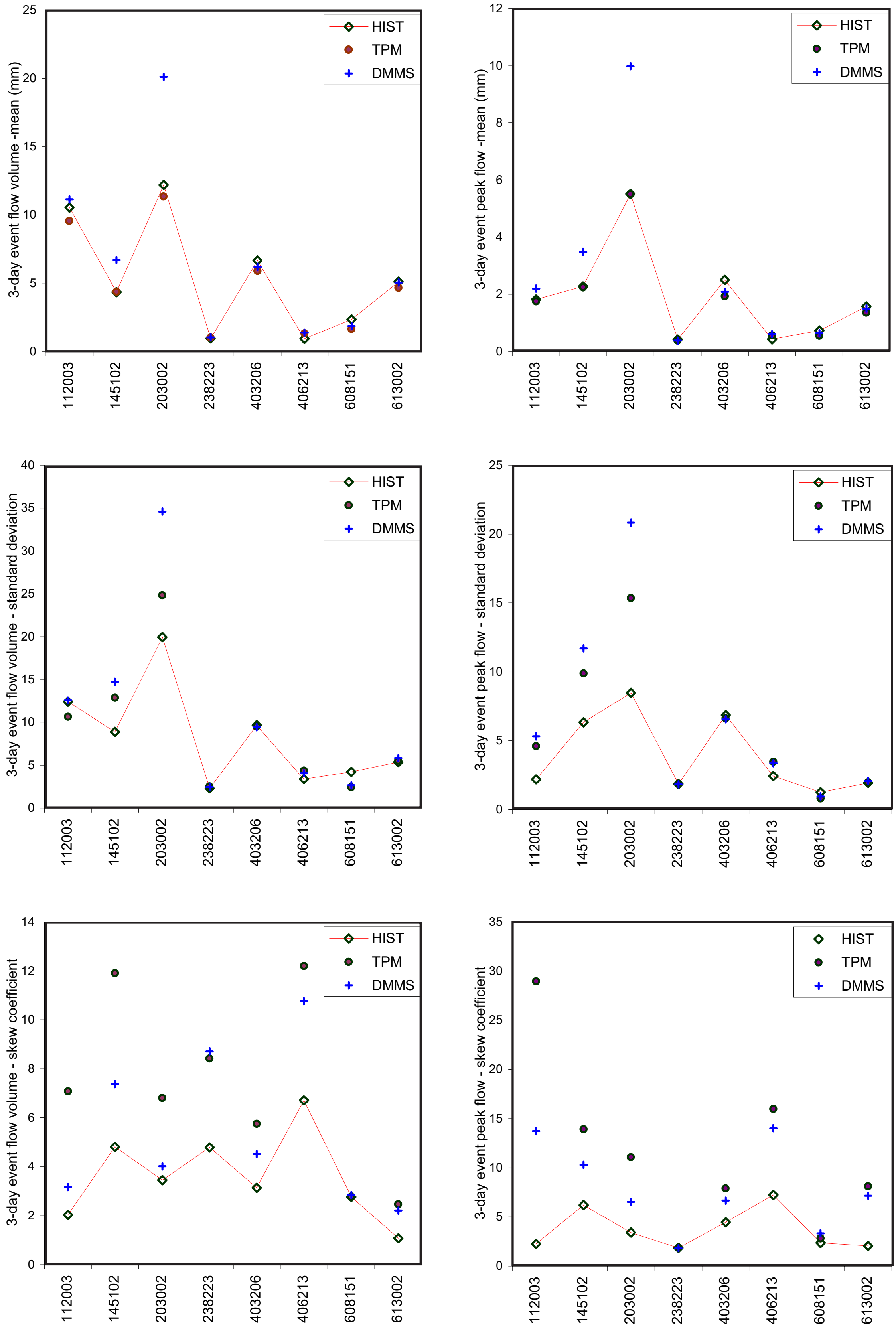


Figure C.6 Comparison of flow duration curves derived by modelling generated rainfall and historical rainfall (continued)



(a) Flow volume (mm)

(b) Peak flow (mm/day)

Figure C.7 Comparison of statistics for 3-day event flow volume and peak flow (mean, standard deviation and skew)

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- Department of Sustainable Natural Resources, NSW
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- Griffith University
- Melbourne Water
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