REVIEW AND DEVELOPMENT OF RAINFALL-RUNOFF MODELLING TOOLS FOR WATER RESOURCE APPLICATIONS IN CYPRUS

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REPORT

to the

Division of Hydrology
Water Development Department
Cyprus

by

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Table of Contents

List of Tables

List of Figures

1 Introduction to the Project and Summary of Results and Conclusions

There has been a long history of rainfall-runoff modelling in Cyprus to support water resource planning and management. This has been based exclusively on a conceptual rainfall-runoff model developed by Mr. F. Mero of Tahal, Israel that was introduced in 1967. The main type of application has been in the extension of flow records by rainfall-runoff simulation, based on the long rainfall records which exist in the island.

Given the long history of the model, and the development of rainfall-runoff modelling technology and software over the last 3 decades, it was felt that the model should be reviewed, and a contract between FAO and Imperial College Consultants Ltd, London (ICON) was put in place. The objectives are:

a) To review the model as currently applied at the Division of Hydrology in Cyprus and consider whether upgrading or replacement is required of the model and/or pre- and post-processing software
b) To propose alternative models which could be applicable for Cyprus, and undertake comparative testing based on case study data from Cyprus
c) On the basis of b) above, and discussions with the Division of Hydrology to recommend the most appropriate course of action for rainfall-runoff modelling in the context of the project
d) To participate in appropriate training of staff of the Division of Hydrology

A project inception visit was made to Cyprus (25-30 August) which resulted in a preliminary report, agreed with the Division of Hydrology, that reviewed the MERO model, the requirements for rainfall-runoff modeling in Cyprus and the state-of-the-art of hydrological modeling. The report defined a programme of comparative analysis of model performance based on the MERO model and a Rainfall Runoff Modeling Toolbox (RRMT) developed at Imperial College, using data-sets provided by the Division of Hydrology. The comparative analysis has now been completed for two contrasting catchments, the Peristerona and the Dhiarizos, and the results are presented in this report. In addition, it was agreed that it would in any event be useful to provide an improved User Interface for the MERO model; this has now been designed and implemented, and is also reported below.

It is concluded that a model from the RRMT with probability-distributed soil moisture accounting and two parallel linear stores (PD4-2PAR) gives generally superior performance to the Mero model for the catchments and performance criteria considered, and has a good degree of parameter identifiability. In contrast, for the Mero model, due to the large number of parameters and the resulting complexity of the parameter space, automatic methods of optimisation are unsuccessful and most of the parameters are non-identifiable. (This precludes development of an objective method to relate model parameters to catchment characteristics for application to ungauged catchments). It is therefore recommended that the RRMT system be adopted for future modelling studies. This system provides powerful state-of-the-art tools for automatic model fitting, performance analysis and parameter and prediction uncertainty analysis.
(User manuals are appended to this report).

For consistency with previous practice, an up-to-date user interface has been provided for the Mero model, allowing more efficient data input and analysis/display of results. The Mero model can therefore be used as required to support further studies and will continue to give good performance for gauged catchments, albeit subject to the limitations that manual calibration is required and there is a high level of parameter uncertainty.

To address the simulation of ungauged catchments, the RRMT can be used to support a programme of regional analysis. This requires model fitting to as many gauged catchments as possible, followed by analysis of model parameters as a function of catchment characteristics. With the automatic capability of the RRMT, this is readily achievable (a recent 4 month MSc study at IC carried out a similar regional analysis based on 23 catchments), and is the logical next step in developing a comprehensive modelling capability for Cyprus.

With respect to training, a seminar on the state-of-the-art of hydrological modeling was given by Prof. Wheater in Cyprus to the Water Development Department, and a member of staff of the Division of Hydrology, and principal modeller, Marilena Panaretou, was seconded to Imperial College for two weeks. During that time she made a significant contribution to the modeling analysis, and received training in the use of the RRMT. In the final consultants' visit to Cyprus, 5-8 December, 2001, handover of the improved Mero modelling software was made, and further training provided.

2 The Modelling Tools

2.1 The Mero model Conceptual Structure

A description and critique of the Mero model was presented in Wheater and Bird, August, 2001. It is based on a perceived conceptual representation of the relevant hydrological processes, and, dependent on current simulated values of soil water storage, runoff is partitioned between surface runoff, interflow and fast and slow groundwater components; evaporation is a function of potential evaporation and current soil water state. A full account is given by Panaretou (1990). The model is relatively complex. The functional relationships between inputs, outputs and the various conceptual stores in the model are defined using empirical relationships which themselves are specified by model parameters. In its basic form there are 17 parameters which require to be defined for the model to run, with variants this can increase to 24 parameters. In application, the catchment can be represented as a number of different zones, each of which requires 17-24 parameters to be specified, thus a 4 zone model requires between 68 and 96 parameters. There is no routing element; flows from different zones are simply accumulated at the outlet. We note general conclusions from the contemporary research literature (e.g. Wheater et al, 1993; Beven, 2000) that while this very large number of parameters may give flexibility in simulating different modes of response, it will inevitably lead to gross uncertainty in the parameters. The concept of equifinality has been used to describe the fact that with complex models and limited calibration information (e.g. a single input (rainfall) and a single output (flow) time-series), many combinations of parameters will give equally good performance. This typically arises if more than 5 or 6 parameters are used; here we may have approaching 100. It is therefore difficult to assign physical significance to those parameters, or to relate them objectively to catchment physical characteristics, as is required for application to ungauged catchments, for example.

2.2 The Rainfall Runoff Modelling and Monte Carlo Analysis Toolboxes (RRMT and MCAT)

One response to the problems associated with parameter uncertainty has been to reduce model complexity with the aim of reducing parameter uncertainty, and to develop a more flexible approach to modelling so that alternative formulations can be readily tested and an appropriate model for the required purpose can be developed. At Imperial College, a Rainfall-Runoff Modelling Toolbox (RRMT) has been developed to support this (Wagener at al., 2001a,b).

A second response has been to attempt to extract more information from the runoff time-series. Most optimisation techniques have traditionally used a single measure of performance (objective function) to define model performance. However, a user experienced in manual optimisation would tend to look for different attributes of the hydrograph in tuning model parameters. This has now been taken up in automatic schemes which use "multi-objective" analysis of model performance, so that, for example, trade-offs between high flow and low flow performance can be formally examined.

A major factor in rainfall-runoff modelling has been the dramatic increase in readily available computing power. This has allowed the development of extremely powerful, computationally-intense, methods of optimisation and analysis. The Shuffled Complex optimisation algorithm (SCE), developed at the University of Arizona, for example, combines a simple Simplex method with a genetic algorithm to identify model parameter values through automatic model fitting. New, stochastic methods of analysis have also been developed whereby a model can be run many thousands of times in a Monte Carlo analysis to investigate parameter sensitivity and parameter uncertainty. This can then be used to add confidence limits to model simulations. These methods have been combined in a Monte-Carlo Analysis Toolbox (MCAT) at Imperial College (Wagener and Lees, 2001). These state-of-the-art tools have been used in the investigation and comparative evaluation presented below.

3 The Programme of Analysis

We are extremely grateful to the Division of Hydrology, and in particular Marilena Panaretou, for providing comprehensive data sets for the Peristerona catchment, which includes two long-term, high quality flow-gauging stations, and the Dhiarizos. These have been the main focus of the model intercomparison studies in which the performance of a range of simple conceptual models has been compared with that of the Mero model.

The simple conceptual models have been assembled using the RRMT, which enables easy running and performance evaluation of many different model structures on a data set. The RRMT builds models from a selection of component modules. Each model has a soil moisture accounting module, which generates effective rainfall from actual rainfall, evaporation (or temperature) and current soil moisture conditions, and a routing module, which determines how effective rainfall is routed. Different combinations of modules build different model structures. Full details of the available modules are given in Wagener et al. 2001c.

For the present analysis, the Mero model has been compiled to run in the Windows environment and the program input interface has been simplified. The user interface of the Mero model has been improved so that model performance can quickly be evaluated using some of the visualisation tools from the RRMT. The original intention was to fit the Mero model using automatic optimisation techniques. However, results using the state-of-the-art SCE optimisation algorithm suggest that this is not feasible for the Mero model due to the dimension and nature of the parameter space. In short, the complexity of the Mero model has defeated what is probably the most advanced optimisation methodology currently available. Hence the model intercomparison results are based on the expert manual calibrations derived by Panaretou.

4 Results for the Peristerona catchment

4.1 Data

The Mero model requires areally-averaged daily rainfall and observed daily flow time series for fitting. Evaporation is accounted for by adjusting historic data from Nicosia averaged over a 5 year period. The RRMT requires daily rainfall, observed flow and evaporation or temperature as time series inputs for model fitting. For fitting RRMT models to the Peristerona catchment, observed flow data were used from gauge 3-7-1-50. Areally- averaged rainfall data as used to fit the Mero model were available for the catchment upstream of gauge 3-7-1-50 and evaporation data from climate stations 310 and 440 were combined with weighting factors. For automatic optimisation of the Mero model flow data from gauge 3-7-1-20 were used together with upstream areally-averaged rainfall. Details of gauge and climate locations can be found in the Water Development Department report (Alexandrou, 1996).

In Cyprus there are ungauged abstractions of water from rivers by individuals. The quantities abstracted are uncertain and the estimated annual amount has been provided for the catchment together with an estimated monthly distribution (Panaretou, pers. comm.). Monthly estimated abstractions have been simply added to the observed flow time series and the models fitted to these data. Although crude, in the absence of more detailed information this method was considered to be the best practicable approach. Clearly this uncertainty will affect model fitting to low flows.

The period for which all of the data time series required for fitting the RRMT models were available runs from 1st January 1986 until 30th September 1994, hence this period was used to fit the RRMT models. The performance of these models was first compared with that of the Mero model for the same period, using 4 zones for the Mero model and the available manual calibration (based on the period 1st October 1977 to 30th September 1989). There are thus two inconsistencies in this comparison; a) a 12 year Mero calibration is compared with a RRMT calibration of less than 9 years, and b) the 1989 to 1994 data lie outside the Mero model calibration period. Hence objective functions were also evaluated for the better performing RRMT models for the period overlapping the Mero fitting period (1st January 1986 to 30th September 1989), so that the second inconsistency could be overcome and a more objective comparison of model performance could be made.

The period of data used for trials of the automatic fitting of the Mero model runs from 1st October 1977 to 30th September 1982.

4.2 *Objective functions used and optimisation of RRMT models*

For objective assessment of a model, numerical measures of performance are required, commonly termed objective functions. The following were used here:

In all definitions *N* is the number of observations, *i* runs from 1 to *N*, *o* are observed values and *c* are calculated values for parameter set θ.

RMSE_SQRT — Root mean square error of square root transformed data

$$RMSE\_SQRT = \sqrt{\frac{1}{N}\sum_i \left(\sqrt{o_i} - \sqrt{c_i(\theta)}\right)^2}$$

RMSE — Root mean square error

$$RMSE = \sqrt{\frac{1}{N}\sum_i \left(o_i - c_i(\theta)\right)^2}$$

NSE* — $1 -$ Nash Sutcliffe Efficiency

$$NSE^* = 1 - \sum_i \left(o_i - c_i(\theta)\right)^2 \Big/ \sum_i \left(o_i - \bar{o}\right)^2$$

FM — RMSE using upper and lower thresholds between which observed flow values at a time step are included in the summation. (Medium Flows.)

FL — As above but using a threshold for observed flows above which contributions are not made to the summation. (Low Flows).

All objective functions used in this study have been defined to take values greater than or equal to zero with zero being the optimal value. This means that the NSE* objective function has been defined as 1 minus the usual NSE definition.

Contributions to an objective function are typically influenced unequally by different features of the hydrograph. For example the RMSE objective function is influenced more by high flows than by low flows, as residual variance for high flows tends to be higher. A response to this is to use a combination of objective functions to evaluate different aspects of model performance. Ideally, parameter sets will be identified for which all objective functions used are good, however trade-offs in model performance can also be examined.

The optimisation procedure adopted for the RRMT was based on Monte Carlo sampling from the feasible parameter space. For a specified candidate model structure, a Monte Carlo simulation with 5000 uniformly sampled parameter sets was run for each objective function (i.e. 25000 model trials) and a best performing subset of parameter sets was identified. The intersection of these subsets then becomes the set of parameter sets performing well with respect to all objective functions used. If the better parameter sets do not intersect, there may be reason to doubt the appropriateness of the model structure. For the RRMT models these best performing parameter sets were then studied further by looking at plots of observed and calculated flow as well as flow duration and cumulative volume plots. Similar performance evaluation of the fitted Mero model output has been undertaken.

4.3 Mero model performance

As noted above, the Mero model has been fitted manually to the Peristerona catchment for the period 1st October 1977 to 30th September 1989. Using these model parameters, flow has been generated for the period 1st January 1986 to 30th September 1994 (the period of overlap of RRMT required data). Using the Mero model output series with the RRMT, it has been possible to calculate objective functions and plot results in exactly the same way as for the RRMT models. Table 1 shows the objective functions evaluated for the Mero model for the RRMT fitting period (as well those evaluated for the RRMT model structures PD4 with 2PAR and BUC with 2PAR, discussed below). As can be seen, the Mero model performance with respect to the objective functions used appears to be comparable for the period during which it was fitted (1/1/86 – 30/9/89) and the period beyond which it was fitted (1/10/89-30/9/94). The higher RMSE value for the earlier period can be accounted for by a high peak (and residual) during that period. In general the high degree of variability of the rainfall process leads to variability in objective function values evaluated for different periods.

Figures 1 and 2 show plots of observed flow and Mero model flow and figure 3 shows flow duration and volumetric fit for the Mero model output for the period of RRMT fitting.

Table 1 Evaluations of the objective functions used for Mero model simulated flow, PD4 with 2PAR and BUC with 2PAR RRMT model structures. Values in red type are lower (i.e. better) than achieved by the Mero simulation.

		Objective Function				
Model	**Period**	**PART I RMSE_SQRT**	**RMSE**	**NSE***	**FM**	**FL**
PART II Mero	1/1/86-30/9/94	0.3015	1.4117	0.4863	1.2373	0.2635
	1/1/86-30/9/89	0.3071	1.7853	0.4648	1.3350	0.2020
	1/10/89-30/9/94	0.2956	1.0498	0.5481	1.5530	0.3041
PD4 with 2PAR	1/1/86-30/9/94	0.2547	1.3525	0.4464	0.9118	0.1741
	1/1/86-30/9/89	0.2694	1.7280	0.4354	0.7279	0.1453
	1/10/89-30/9/94	0.2534	0.9667	0.4860	1.0494	0.2121
BUC with 2PAR	1/1/86-30/9/94	0.3524	1.4140	0.4879	0.9343	0.1590
	1/1/86-30/9/89	0.3796	1.8099	0.4777	0.8318	0.1575
	1/10/89-30/9/94	0.3070	0.9766	0.4961	0.9777	0.1666

4.4 RRMT Model combinations

In section 4.3 a method to obtain a best subset of parameter sets with respect to all objective functions used was described. This method was used to explore model structures for the Peristerona catchment using different combinations of RRMT modules. The soil moisture accounting modules investigated were:

Catchment Wetness Index (CWI)
Catchment Moisture Deficit (CMD)
Bucket Store (BUC)
Probability Distribution of Moisture Stores (PD4)

and the routing modules explored were:

Conceptual Linear Reservoir (CRES)
Two Conceptual Linear Reservoirs in Parallel (2PAR)
Leaky Aquifer Model Structure (LEAK)

Details of all the above modules can be found in the RRMT user manual (Wagener, et al.,2001c), appended to this report. It can be noted that the CWI method is as widely used in the commercial IHACRES package, and that the PD4 model is the basis of a simulation model developed by Moore at the Institute of Hydrology, Wallingford, widely-used in UK practice.

All permutations of the above modules (i.e. choosing one soil moisture module and one routing module) were investigated using Monte Carlo simulation analysis as outlined in section 4.2, i.e. 12 separate model structures. As discussed below, it was found that for the Peristerona catchment the best performing model structure, in terms of objective function values and parameter identifiability, combined the PD4 soil moisture accounting module with the 2PAR routing module.

The PD4 module repesents storage as a continuum of different sized stores. When stores are full their overflow contributes to runoff. When storage exceeds a maximum capacity all rainfall contributes to runoff. Parameters for the PD4 module are the maximum storage capacity and a shape parameter for the distribution of stores. The 2PAR module routes runoff through two parallel reservoirs with different time constants. Parameters for the 2PAR module are the time constants for each reservoir and the fraction of runoff going through the quicker reservoir. Full details of these modules are found in the RRMT user manual (Wagener et al., 2001c).

4.5 Performance of different RRMT model structures

Table 2 lists the objective function values for all model structures used evaluated during the RRMT fitting period. In all tables, those objective function values which are better than the Mero model results are indicated in red type. Several model structures perform well on the basis of objective function evaluations alone. The structures PD4 with 2PAR, PD4 with LEAK, BUC with LEAK, CMD with 2PAR, CMD with LEAK and CWI with 2PAR outperform the Mero model in terms of every objective function used. However it is an aim here to find a model structure with identifiable parameters as well as good performance, in particular to support regionalisation..

Of the soil moisture accounting modules used only the PD4 and BUC modules (with 2 and 1 parameter respectively) combine with routing modules to give model structures with identifiable soil moisture module parameters. Although the CMD and CWI modules perform well numerically in some model structures they are rejected on the basis of their lack of identifiability. It is likely that these rejected modules have too many parameters (5 and 6 respectively) to be identifiable here. The LEAK routing module is similarly unidentifiable and is also rejected. The CRES routing module uses a single conceptual reservoir to represent routing. This leads to inadequate simultaneous modeling of low flows and high flows by a single set of reservoir parameters (and hence single time constant) which is reflected numerically (table 2) and was also noticed when looking at the recessions of the simulated hydrograph.

This leaves two candidate model structures. PD4 with 2PAR and BUC with 2PAR. Figures 4 to 9 show plots of RRMT model generated flow together with observed flow and Mero model generated flow for the PD4 with 2PAR model structure and the BUC with 2PAR structure and plots of the volumetric fits and flow duration curves for these model structures. Both structures are parsimonious in the number of parameters used (5 and 4 respectively) and appear identifiable as is seen in figures 10 to 19 which, with dotty plots, show parameter identifiability for these model structures for each objective function used. These figures represent the results from the multivariate Monte Carlo sampling, with individual parameter sets represented as individual points. They therefore display graphically whether there is a uniquely identified optimum for a given parameter, or conversely whether the successful parameter values are widely distributed across the parameter space. It should be noted that for the PD4 with 2PAR and BUC with 2PAR model structures, dotty plots are included for the parameters init. c and init. def. respectively. These parameters describe the initial soil moisture status. As the first 5% of the time series (about 160 days) are excluded from the objective function evaluation to allow for warm-up, these are strictly not fitted parameters and have limited impact on the simulation (they could be optimised later having identified the other parameter values). Hence the number of free parameters for the PD4 with 2PAR model structure is 5 and the number for the BUC with 2PAR model structure is 4.

The flow duration curve and volumetric fit for the PD4 with 2PAR model structure are better than those achieved by the Mero model (figures 3 and 6) whilst the same curves are poor for the BUC with 2PAR structure . The BUC module generates effective flow if a simple conceptual bucket is full. If this threshold is not reached there is no flow to be routed and periods of flow may be missed by the model. In contrast the PD4 module repesents storage as a continuum of different sized stores and hence thresholds. It is decided that the PD4 module is therefore more appropriate than the BUC module, which is also noticed in the numerical comparisons of tables 1 and 2.

Parameter values used for the PD4 with 2PAR model structure to obtain the results here are given below.

Cmax	b	k(q)	k(s)	%(q)
315.3441	0.3413	3.7078	42.0478	0.6359

Figures 20 and 21 show multi-objective plots for the PD4 with 2PAR and BUC with 2PAR models respectively for all objective functions used. Notice that there is a trade-off between the performance of low and medium flow objective functions and that of the other objective functions for both model structures. This is more pronounced for the BUC with 2PAR model structure possibly because the simple bucket soil moisture store representation is unable to capture the low and high flow regimes of the hydrograph simultaneously.

The PD4 with 2PAR model structure uses only 5 parameters and performs, for this catchment, at least comparably to the Mero model fitted to 4 zones each having between 18 and 24 parameters. The PD4 with 2PAR model also shows parameter identifiability which the Mero lacks as will be seen in section 4.6.

Table 2 Evaluations of the objective functions used for different RRMT model structures. Values in red type are lower (i.e. better) than achieved by the Mero simulation.

Objective Function Evaluation for different RRMT models (fitting period 1/1/86-30/9/94)					
	Objective Function				
Model Structure	RMSE_SQRT	RMSE	NSE*	FM	FL
PD4 2PAR	0.2547	1.3525	0.4464	0.9118	0.1741
PD4 CRES	0.2708	1.4166	0.4856	1.0119	0.1236
PD4 LEAK	0.2435	1.2037	0.3506	0.7186	0.0927
BUC 2PAR	0.3949	1.4883	0.5405	0.5810	0.0264
BUC CRES	0.4018	1.6020	0.6210	1.0212	0.1287
BUC LEAK	0.2993	1.2703	0.3905	0.7255	0.1110
CMD 2PAR	0.2853	1.2290	0.3655	0.6165	0.1110
CMD CRES	0.3203	1.3633	0.4498	0.7409	0.1247
CMD LEAK	0.3000	1.2758	0.3829	0.5371	0.0955
CWI 2PAR	0.2538	1.4170	0.4859	0.9824	0.1783
CWI CRES	0.2617	1.5060	0.5488	0.8454	0.1660
CWI LEAK	0.3044	1.4015	0.4753	0.6384	0.0959

4.6 Automatic Optimisation of the Mero Model

Attempts were made to use automatic optimisation algorithms to fit the Mero model parameters. The two methods used were Monte Carlo Simulation and the Shuffled Complex Evolution algorithm (Duan, Gupta and Sorooshian, 1993 and Duan, Sorooshian and Gupta, 1994). The catchment used for optimisation was that upstream of flow gauge 3-7-1-20 for the period 1st October 1977 to 30th September 1982. Areally averaged upstream rainfall was used together with evaporation inputs as used in previous Mero model fitting. This catchment was chosen for automatic optimisation as the Mero model has previously been fitted to it using a single zone which means that the number of parameters and hence the dimension of the parameter space is limited, although still large.

In Monte Carlo simulation, as described above, parameter sets are generated by independently sampling parameters from uniform distributions whose bounds are specified by the user. These parameter sets are used to run the model and generate an output series which can be used with observed flow data to evaluate model performance using appropriate objective functions. As before, a subset containing the best parameter sets can be obtained as the intersection of those subsets containing the best parameter sets with respect to each objective function. A sample size of 99999 parameter sets was generated and a threshold was applied to reject parameter sets with RMSE_SQRT objective function values above 0.12 so that all parameter sets were in some way plausible. Despite this the best performing sets of parameters failed to represent some important features of the hydrograph. Figure 22 shows a typical plot of model generated flow together with observed flow for the simulation period. It is noted that the simulated hydrographs lack the variability of the observed hydrograph. It is suggested that the dimension and nature of the parameter space inhibit automatic model optimization. It is possible that results would be better if an experienced user of the Mero model were able to fix some parameters to reasonable values for a given catchment and narrow the boundaries for others. Figure 23 shows dotty plots for the 18 free parameters used in the Montecarlo simulation described above. It should be noticed firstly that the density of points with low objective function value is low, suggesting that points repesenting good parameter sets are sparcely distributed in the parameter space and secondly that these points are not localised in the parameter space indicating poor identifiability of the parameters.

The Shuffled Complex Evolution (SCE) algorithm, developed at the University of Arizona, has been successfully used to optimize the US National Weather Service hydrological models. The algorithm uses the combination of a set of local Simplex searches together with global sharing of information in the parameter space. This is achieved by simultaneously evolving different groups of points in the parameter space and allowing communication between groups by occasionally rearranging (i.e. shuffling) the grouping of all points in the parameter space according to their objective function values. This has proved to be an efficient optimization tool and often outperforms simpler gradient search methods (Duan, Sorooshian and Gupta, 1994). Attempts were made to locate parameter sets for the Mero model using the SCE algorithm. The three objective functions used in these attempts were RMSE_SQRT, RMSE and NSE. For each of these results are similar to those of Monte Carlo simulation. The search process terminates when the groups of points converge into a small region of the parameter space and the plotted flow series lack the variability seen in the observed flow series as is seen in figure 24. This suggests that the search method is performing no better than the Monte Carlo simulation method, which may reflect a sparsely distributed set of good parameter sets.

In conclusion, the methods used for automatic optimization of the Mero model have proved unsuccessful, probably due to the dimension and nature of the parameter space.

5 Results for Dhiarizos Catchment

In addition to the Peristerona catchment, data from the 263.7 km^2 Dhiarizos catchment on the south side of the island was also used for model inter-comparison. The Dhiarizos catchment can be considered as lowland, with a predominantly sedimentary geology, and the river flows over permeable drift deposits. It can therefore be considered as a contrasting and complementary test case to the Peristerona catchment. Due to the lowland permeable characteristics the catchment is considered potentially to be more difficult to simulate, with aquifer and groundwater processes having a larger role in the system dynamics. The toolbox was used in the same fashion as the Peristerona modelling exercise with different model structures evaluated using Monte Carlo analysis. The models were run for 5000 independent simulations using parameter values estimated from predetermined boundaries to the parameter space. The model structures that were tested are given below.

Soil Moisture Accounting Modules

- Bucket Store (BUC)
- Catchment Moisture Deficit (CMD)
- Catchment Wetness Index (CWI)
- Probability Distribution of Moisture Stores (PD4)

Routing Modules

- Conceptual Linear Reservoir (1RL)
- Two Conceptual Linear Reservoirs in Parallel (2PAR)
- Leaky Aquifer Model (LEAK)

The models were evaluated with respect to the same 5 objective functions used in the Peristerona modelling exercise.

Objective Functions

- Root Mean Square Error of square root transformed data (RMSE_SQRT)
- Root Mean Square Error (RMSE)
- 1 - Nash Sutcliffe Efficiency (NSE*)
- Root Mean Square Error of Low Flow (FL) – below 0.2mm/day
- Root Mean Square Error of Medium Flow (FM) – above 0.2mm/day and below 1mm/day

The catchment was modelled using flow data from the gauging station 1-2-7-90 and evaporation data collected from the Nicosia climatic station. The period that has been simulated covers 20 years from the 1st October 1969 to the 31st September 1989 and has subsequently been subdivided into two separate time series (1/10/1969-31/9/1979 and 1/10/1979-31/9/1989).

To allow comparison of the RRMT and Mero results, the Mero model output has to be evaluated with respect to the 5 objective functions for the aforementioned periods. These results, based on the available manual calibration, are shown in Figures 25 and 26 and summarised in Table 3 below.

Table 3 also includes the objective function values obtained using the RRMToolbox (those models that perform better with respect to objective function values are shown in red). The

RRMT model results are those that give the best performance over all the objective functions and not the global optimum with respect to each individual statistical measure. As for the Peristerona application, the results were obtained by identifying the best performing subsets of parameter values with respect to each objective function. The intersection of these subsets then becomes the set of parameter sets performing well with respect to all objective functions used.

Table 3 Objective function values obtained for the Mero and RRMToolbox models; those RRMT results that are 'better' than the Mero model objective function are indicated in red.

Model	RMSE_SQRT	RMSE	NSE*	FL	FM
MERO (69-79)	0.3756	1.1343	0.5148	0.1578	0.3232
MERO (79-89)	0.4464	1.7473	0.5712	0.1495	0.3056
BUC-1RL (69-79)	0.3659	1.0117	0.4095	0.14	0.6121
BUC-1RL (79-89)	0.3557	1.5156	0.4297	0.0571	0.4805
BUC-2PAR (69-79)	0.3553	0.9099	0.3313	0.0736	0.5757
BUC-2PAR (79-89)	0.358	1.3734	0.3528	0.382	0.532
BUC-LEAK (69-79)	0.3786	0.9912	0.3931	0.0615	0.5085
BUC-LEAK (79-89)	0.4061	1.3572	0.3446	0.0393	0.475
CMD-1RL (69-79)	0.378	1.0349	0.4286	0.0991	0.5667
CMD-1RL (79-89)	0.3737	1.5353	0.441	0.0501	0.521
CMD-2PAR (69-79)	0.367	0.9661	0.3735	0.0667	0.4136
CMD-2PAR (79-89)	0.3495	1.37	0.3511	0.0431	0.5504
CMD-LEAK (69-79)	0.35	0.9891	0.3915	0.0858	0.5204
CMD-LEAK (79-89)	0.3626	1.3448	0.3448	0.0468	0.5063
CWI-1RL (69-79)	0.3279	0.9737	0.3793	0.2241	0.5447
CWI-1RL (79-89)	0.3737	0.1535	0.441	0.0501	0.521
CWI-2PAR (69-79)	0.314	0.8892	0.3164	0.1894	0.5225
CWI-2PAR (79-89)	0.3191	1.2513	0.2929	0.1971	0.5715
CWI-LEAK (69-79)	0.3009	0.8998	0.324	0.0939	0.3254
CWI-LEAK (79-89)	0.2811	1.2614	0.2977	0.0594	0.3154
PD4-1RL (69-79)	0.2833	0.926	0.3431	0.1269	0.353
PD4-1RL (79-89)	0.3052	1.3624	0.3472	0.0816	0.3192
PD4-2PAR (69-79)	0.2793	0.8364	0.2797	0.1201	0.3404
PD4-2PAR (79-89)	0.3005	1.2901	0.3114	0.0771	0.3432
PD4-LEAK (69-79)	0.2856	0.8742	0.3058	0.0997	0.393
PD4-LEAK (79-89)	0.313	1.2837	0.3083	0.0623	0.3497

The RRMToolbox consistently outperforms the Mero with respect to 4 of the 5 objective functions used above. This can be further observed in the bar charts shown below for periods 1/10/1969-31/9/1979 and 1/10/1979-31/9/1989 (Figure 27). It is thus evident that overall the RRMT models perform better than the Mero model. However, when considering medium flows (between 0.2 and 1 mm/day) the Mero model performance is marginally better than the best of the RRMT derived models. However if the modeller were to calibrate the RRMT derived models solely with respect to the FM criteria the models would perform better than the Mero with respect to medium flows. This aspect is addressed further later in the report, when considering the optimum model structure in more detail.

For clarity in the comparative analysis of model performance, we focus on one objective function, the RMSE, and the associated parameter identifiability. Figure 28 shows a bar chart of the optimum RMSE values obtained via the Monte Carlo simulation of all model structures for the period 69 to 79.

Clearly the models with the best RMSE performance are the CWI-2PAR and the PD4-2PAR. However, to identify which of the models is 'better' than the other at modelling the system, parameter identifiability must also be considered. This will affect the uncertainty in simulation of gauged catchments, and will be a dominant factor in the application of the models to ungauged catchments.

The parameter identifiability can be observed via the MCAToolbox dotty plots. The dotty plots for the models PD4-2PAR and CWI-2PAR with respect to RMSE are shown in Figures 29 and 30. The model PD4-2PAR clearly demonstrates better parameter identifiability when compared with the results for the model CWI-2PAR. Of the 5 model parameters (excluding the initial condition), 4 are well identified, with k(s) less so.

The identifiability of parameter values for the PD4-2PAR model with respect to the other 4 objective functions used in this investigation is shown in Figures 31, 32, 33 and 34. This shows, for example that k(s) is well identified using the RMSE_SQRT criterion, and that some trade-offs occur in the optimum parameter values for different criteria.

Ultimately it is up to the modeler to determine which aspects of the system are deemed to be most important for a given application. The trade-offs between different objective functions are more clearly illustrated in Figure 35, again for the model PD4-2PAR with multi-objective plots taken from the period 1969 to 1979.

To address further the question of calibrating the model with respect to medium flows, it is noted that 62 of the 5000 simulations in the Monte Carlo framework give a better fit than the Mero model with respect to the RMSE of medium flows. If the model is now calibrated (for the period 69 to 79) solely with respect to the medium flow criteria the parameters and objective function values are those shown below in Table 4.

Table 4 Parameter and objective function values obtained when the model PD4-2PAR is calibrated to the FM criterion (1969 to 1979).

Cmax	B	Init.c	K(q)	N(q)	K(s)	N(s)	%q
387.7412	0.203	47.6744	8.8606	1	48.3288	1	0.75

RMSE_SQRT	RMSE	NSE	FL	FM
0.3122	1.008	0.4066	0.1161	0.2622

As can be seen, all objective function values are lower than those obtained by the Mero model (Table 3). The percentage differences between the results of the Mero model and the PD4-2PAR model calibrated with respect to medium flows are tabulated below (Table 5).

Table 5 Percentage differences between the Mero model and the PD4-2PAR model using parameters performing best with respect to FM objective function (1969 to 1979).

% Difference RMSE_SQRT	% Difference RMSE	% Difference NSE	% Difference FM	% Difference FM
17	11	21	26	19

In conclusion, it is evident that these results confirm those of the Peristerona catchment. The RRMToolbox and especially the model structure PD4-2PAR simulate the Dhiarizos in a more efficient manner with respect to the physically based data intensive Mero model. Although the criterion of model performance should be selected with a particular task in mind, Table 6 gives the best overall parameter set with respect to all objective functions from the Table 3 results. Figure 36 shows plots of calculated and observed flows for the model using these parameters and Figure 37 shows flow duration and volume fit.

Table 6 The parameter set identified as giving the best overall fit with respect to all objective functions (1969 to 1979).

Cmax	B	Init.c	K(q)	N(q)	K(s)	N(s)	%q
288.1175	0.1529	168.7845	3.8518	1	30.6792	1	0.6853

6 Improving the Mero Model User Interface

Currently the Mero model user interface requires the user to type filenames for every model run and the performance evaluation of model output is indirect involving the use of post-processing programs and then visualization tools. Here the Mero user interface has been modified as follows:

- The Mero model has been compiled to run in the Microsoft Windows environment rather than in DOS. The Windows version of the Mero model accepts data input files in a column format rather than the awkward original format of the Mero model.
- The user is given the choice of either reading parameter values from the old Mero parameter file or from a new parameter file in which the parameters are written in a column. The new format enables faster adjustment of model parameters when fitting whilst the old format enables existing files to be used to repeat previous runs.
- Input and output filenames are now read from a file by the Mero model rather than typed by the user. This means that for multiple runs of the Mero model the filenames are only typed once by the user.
- A direct interface has been created which links the Mero model output file directly to some of the visualization and performance evaluation tools of the RRMT including some plots and objective function evaluation. This gives the Mero model user direct access to a range of tools without the need to post-process output files.
- Executables have been created to generate files written in the new Mero format from files written in the old Mero format enabling previous model runs to be repeated if necessary.

Figure 38 shows the interface linking the Mero model output and the RRMT visualization tools. The user simply opens an output file using the Select Input File button and selects different visualization options by clicking the buttons.

7 Conclusions and Recommendations

An aim of this study has been to undertake a comparative performance analysis of the Mero model and the simple conceptual RRMT modular models. It has been found that, for the Peristerona catchment, the PD4 with 2PAR model structure performs at least as well as the Mero model in terms of objective functions used and flow duration and volumetric fit curves. The PD4 with 2PAR model also has more identifiable parameters and so may be automatically optimised and may have potential for regionalisation, both of which the Mero model lacks. Similar results hold for the Dhiarizos catchment using the PD4 with 2PAR model structure.

As RRMT model performance has been good for these catchments it is recommended that further performance analysis should be done for other catchments to assess potential for regionalisation of the RRMT models in Cyprus. It is recognised that catchments with high transmission losses are particularly difficult to model and it may be that both the RRMT models and the Mero model perform less well in these types of catchment without explicit loss information. However, analysis undertaken for the Dhiarizos catchment suggests that some of the simpler RRMT model structures may perform as well as the Mero model for these catchments, in particular the PD4 with 2PAR structure.

The interface of the Mero model has been improved to make fitting more efficient. There is now no keyboard input when running the model and parameters are read from a file which is easier for the user to update than previously. This makes running the model with different parameter sets easier. A user interface has been created which enables quick performance analysis of the Mero model using some of the plotting facilities and objective functions of the RRMT as well as generates some model output statistics. Some of the original Mero model input file formats are unwieldy and new formats have been used for the updated Mero model. Preprocessing programs have been written to generate input files for the updated model from original Mero input files and these will be delivered.

The specific deliverables from this project are the IC modelling tool-boxes RRMT and MCAT, and an improved user interface for the Mero model. The choice of models therefore lies with the Division of Hydrology. However, it is our strong recommendation that attention should be focussed on the use of the simpler RRMT models, which

a) give equivalent or superior performance to the Mero model,
b) allow automatic calibration and,
c) given the demonstrated identifiability of the parameters, should provide a suitable basis for regionalisation studies, to enable ungauged catchments to be simulated.

8 References

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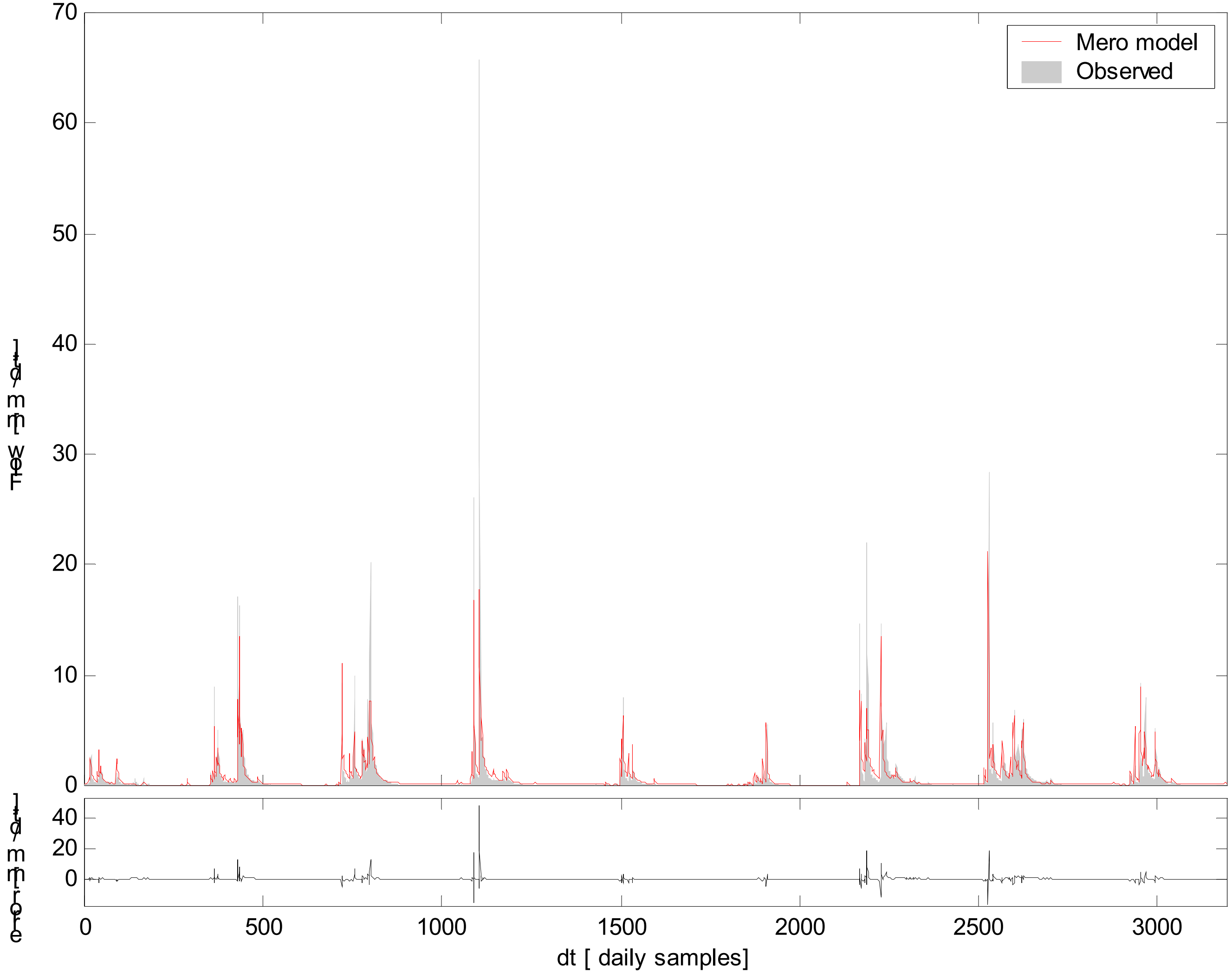
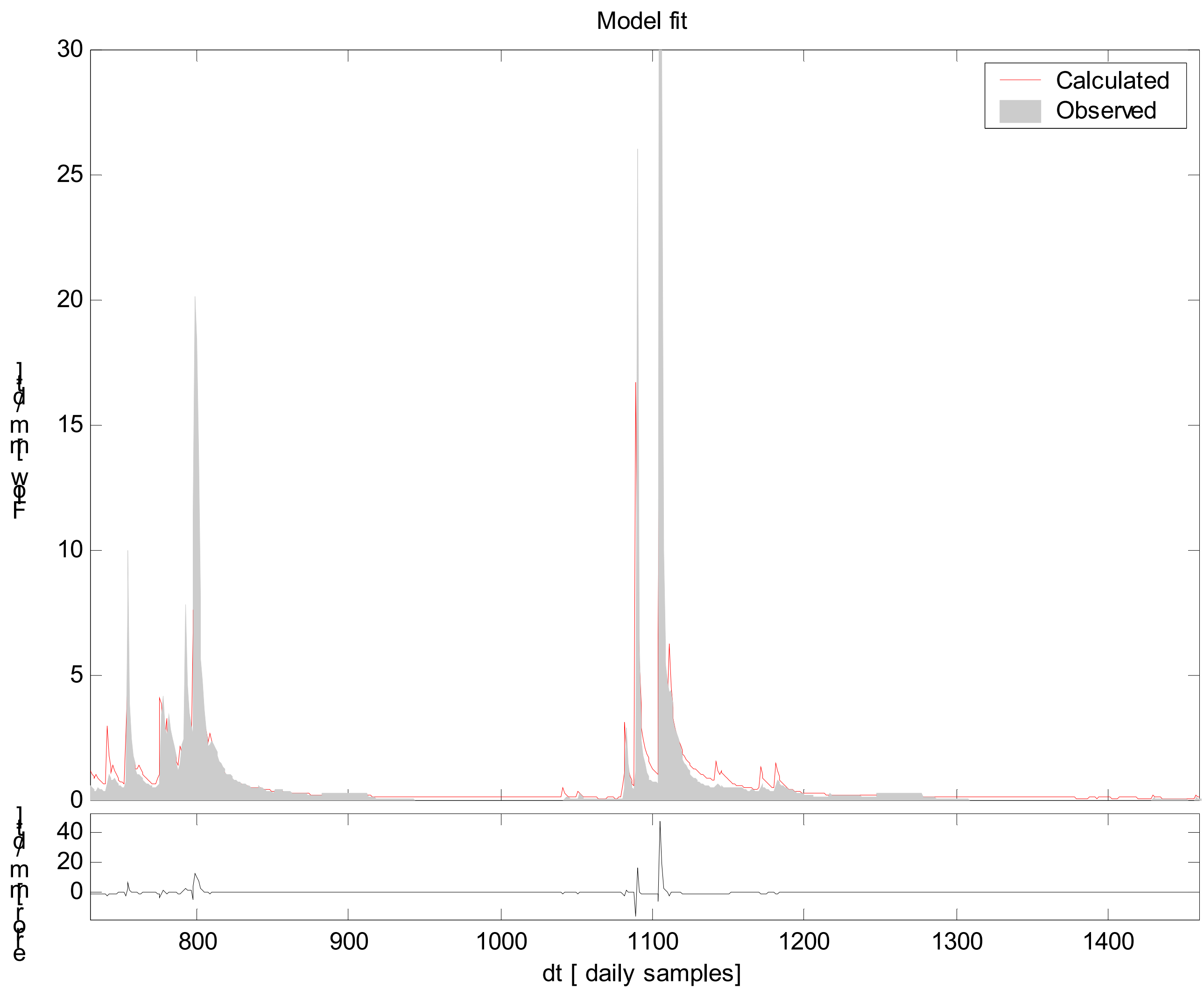
FIGURES

Figure 1



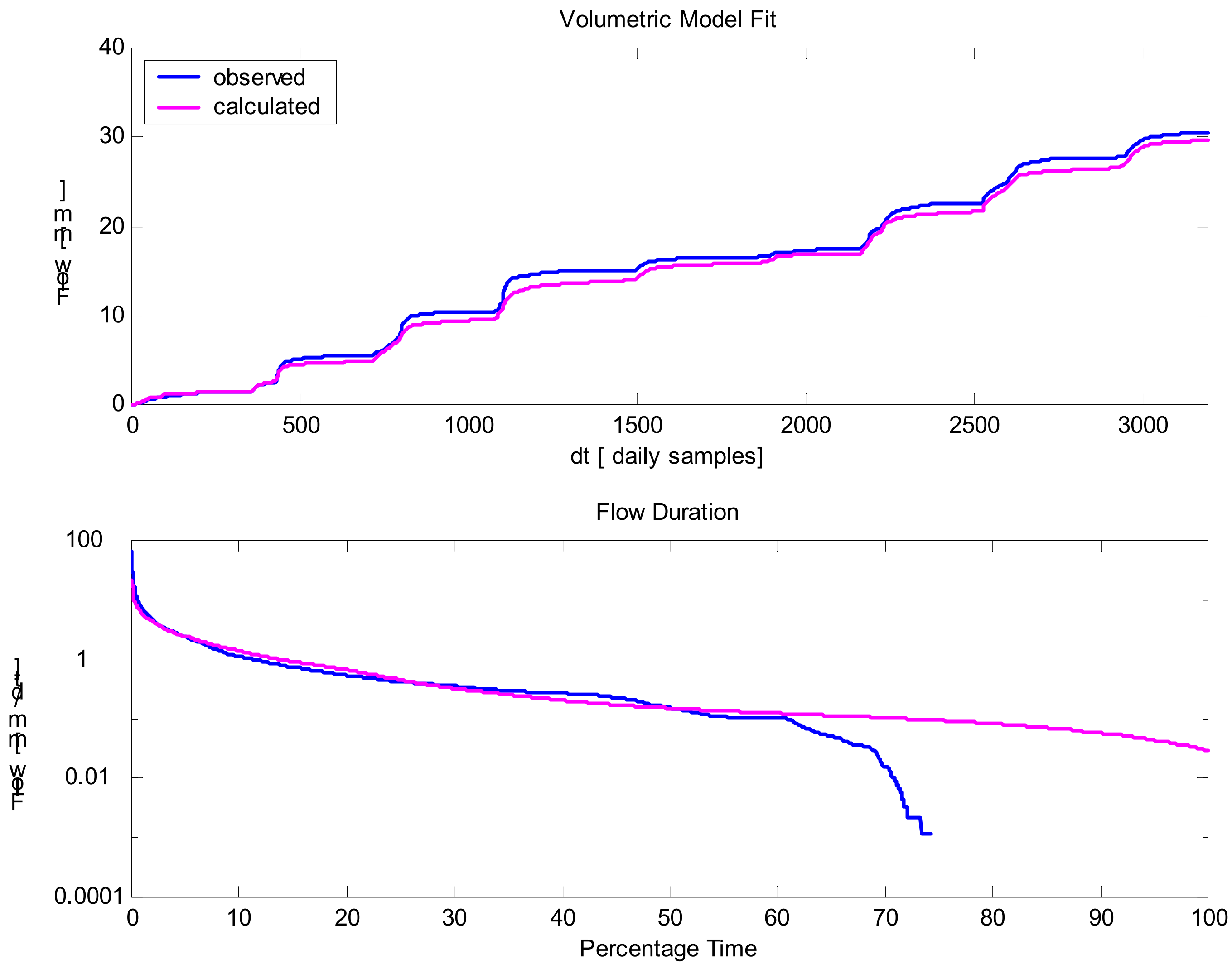
Peristerona: Mero model output flow plotted against observed flow for the RRMT fitting period.

Figure 2



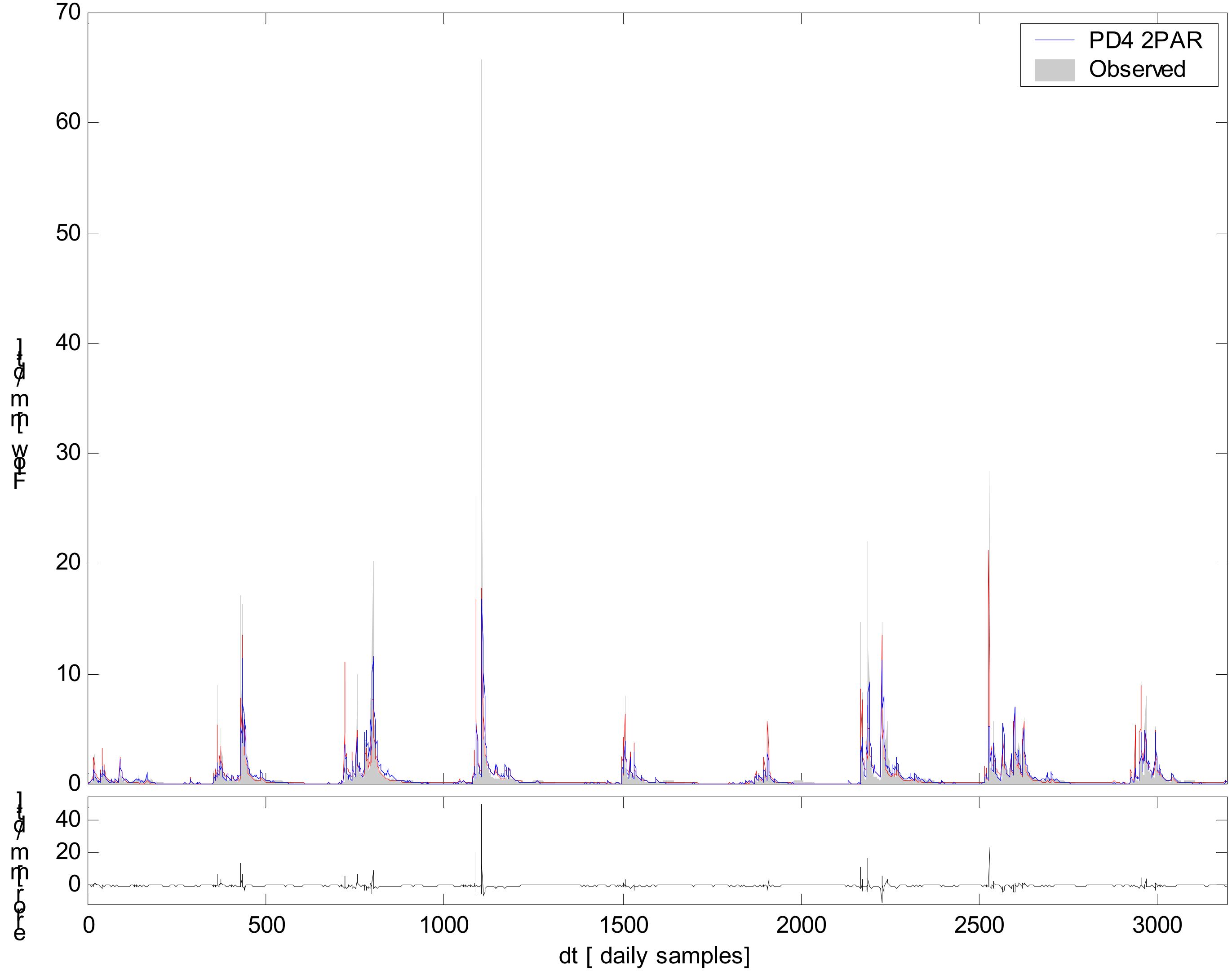
Peristerona: Mero model output flow plotted against observed flow during a 2 year sub-period (RRMT fitting period days 730 to 1460).

Figure 3



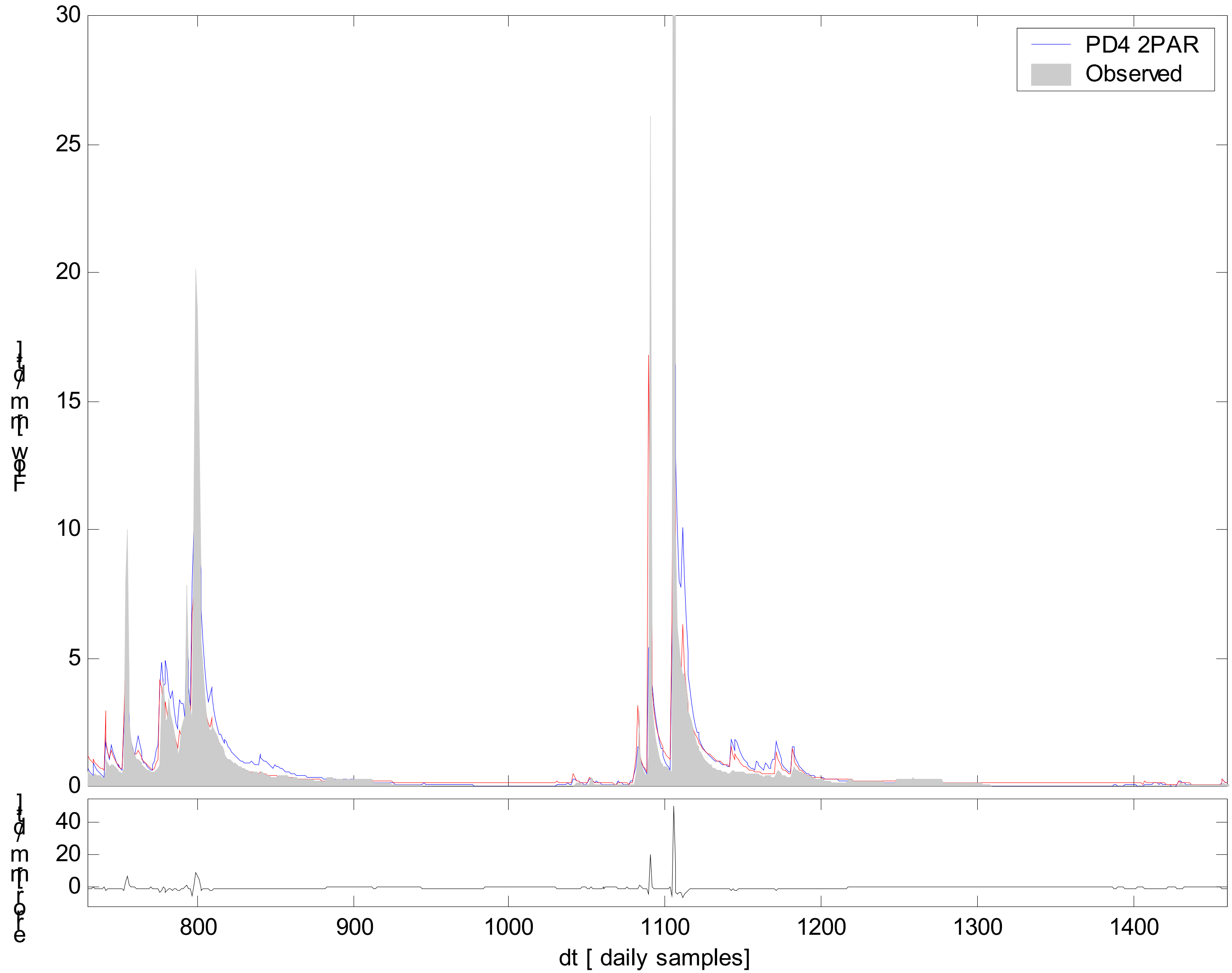
Peristerona: Flow duration and volumetric fit for the Mero model output for the period of RRMT fitting.

Figure 4



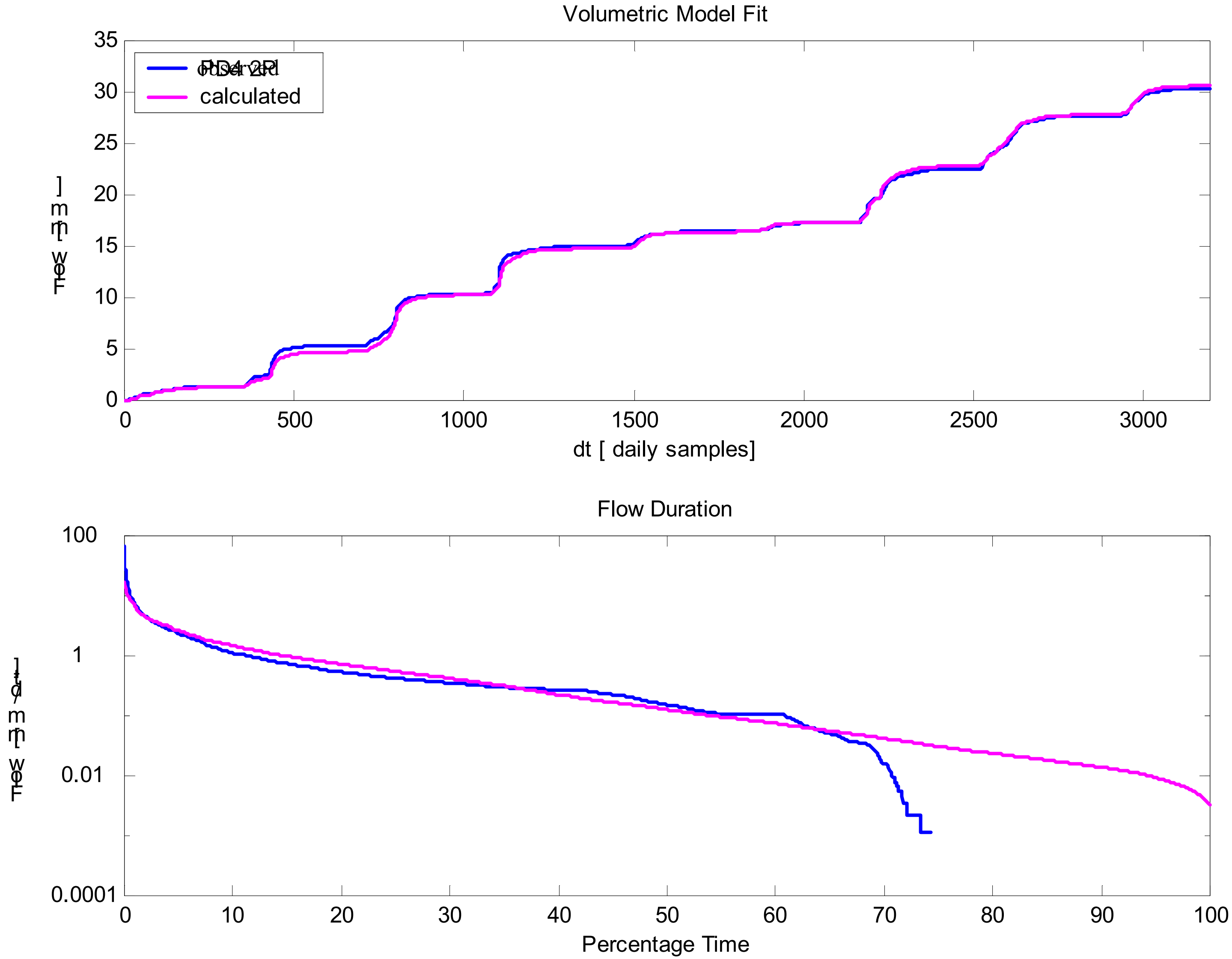
Peristerona: PD4 with 2PAR RRMT model structure calculated flow plotted against observed flow for the entire RRMT fitting period. The red line shows Mero model flow.

Figure 5



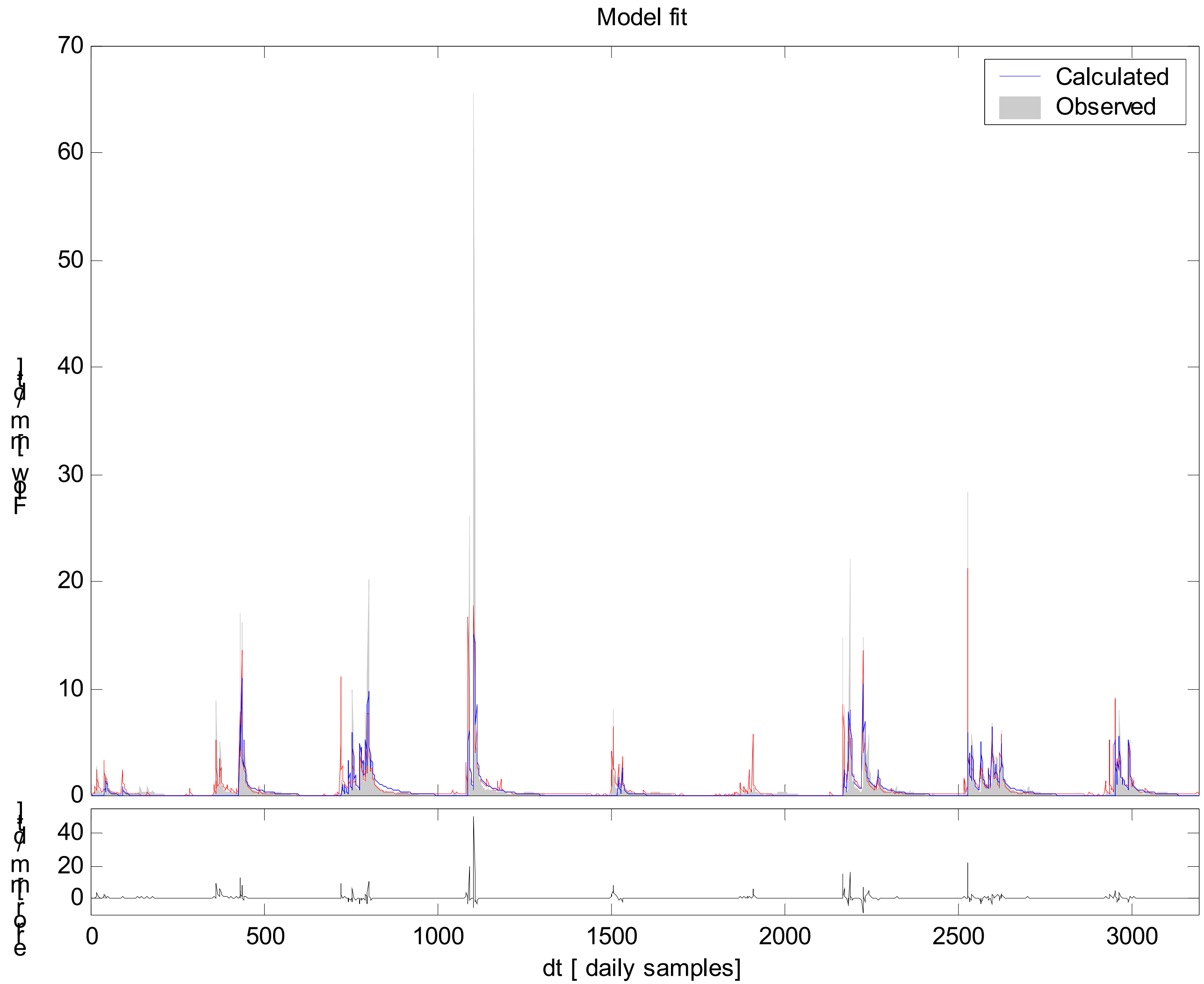
Peristerona: PD4 with 2PAR RRMT mode structure calculated flow plotted against observed flow for RRMT fitting period days 730 to 1460.
The red line shows Mero model flow.

Figure 6



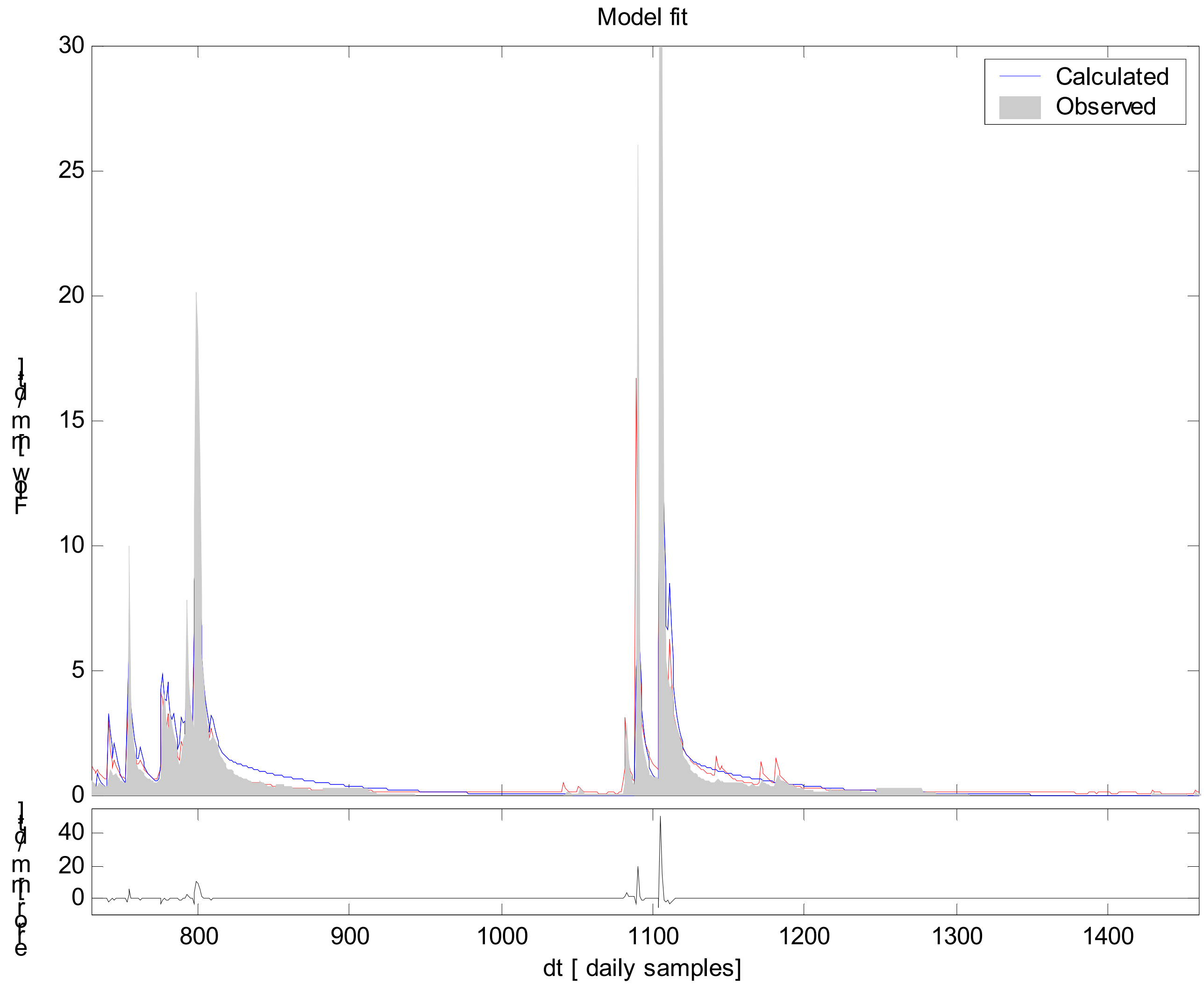
Peristerona: Volumetric fit and flow duration curve for the PD4 with 2PAR RRMT model structure.

Figure 7



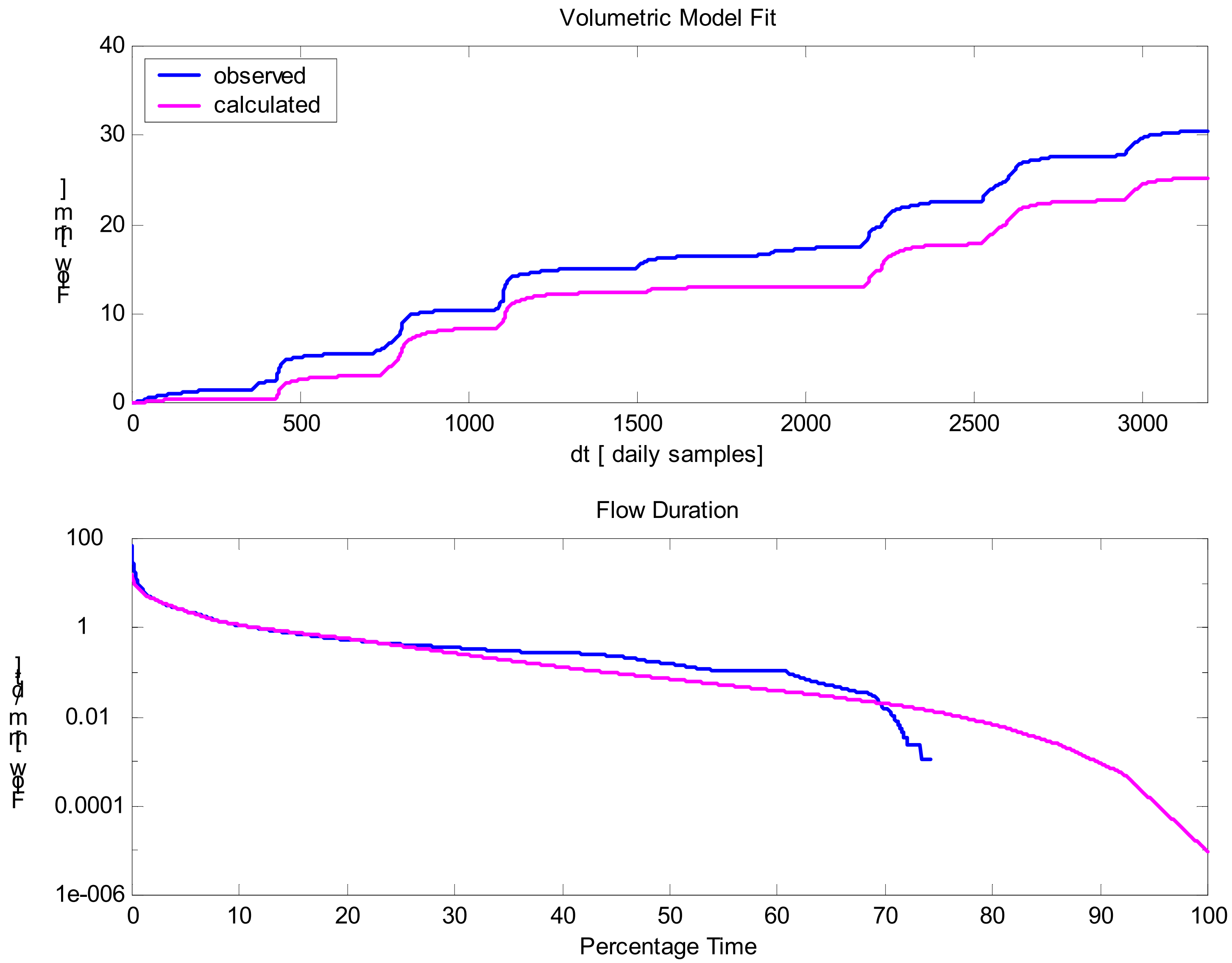
Peristerona: BUC with 2PAR RRMT model structure calculated flow plotted against observed flow for the entire RRMT fitting period. The red line shows Mero model flow.

Figure 8



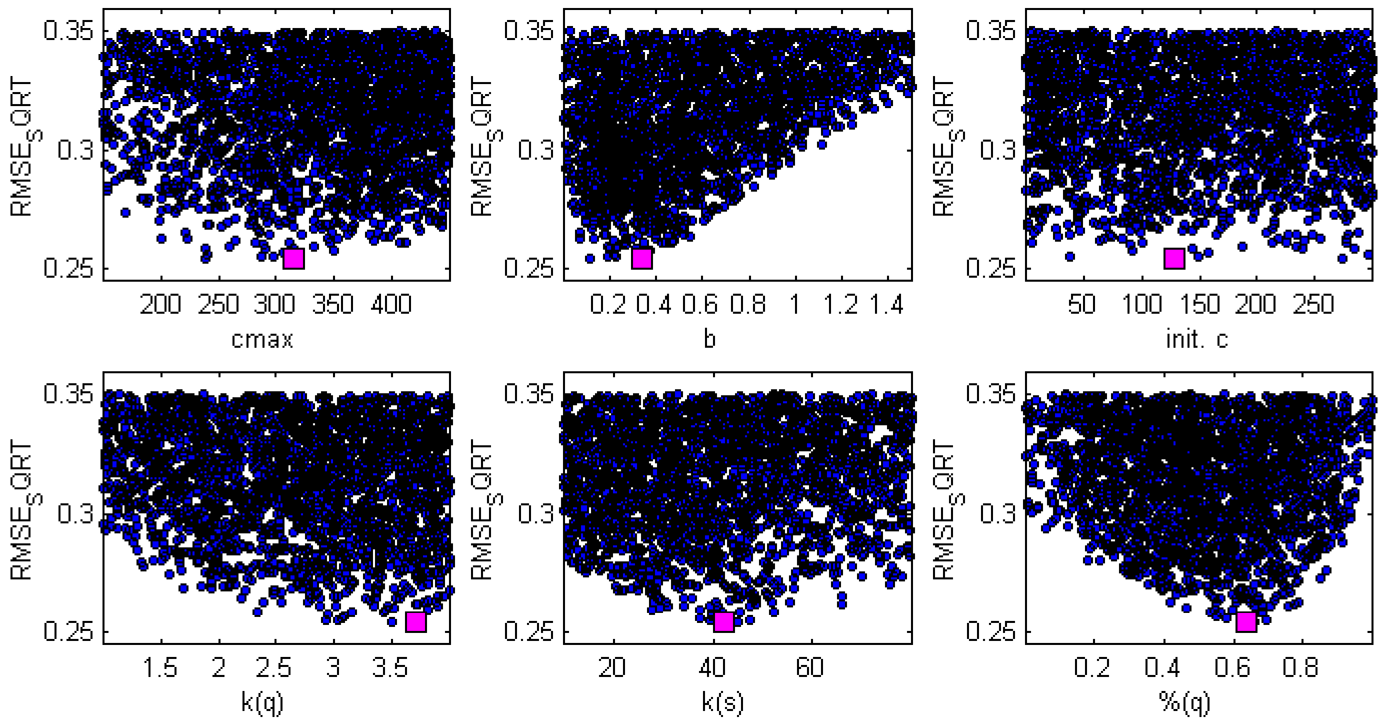
Peristerona: BUC with 2PAR RRMT model structure calculated flow plotted against observed flow for RRMT fitting period days 730 to 1460. The red line shows Mero model flow.

Figure 9



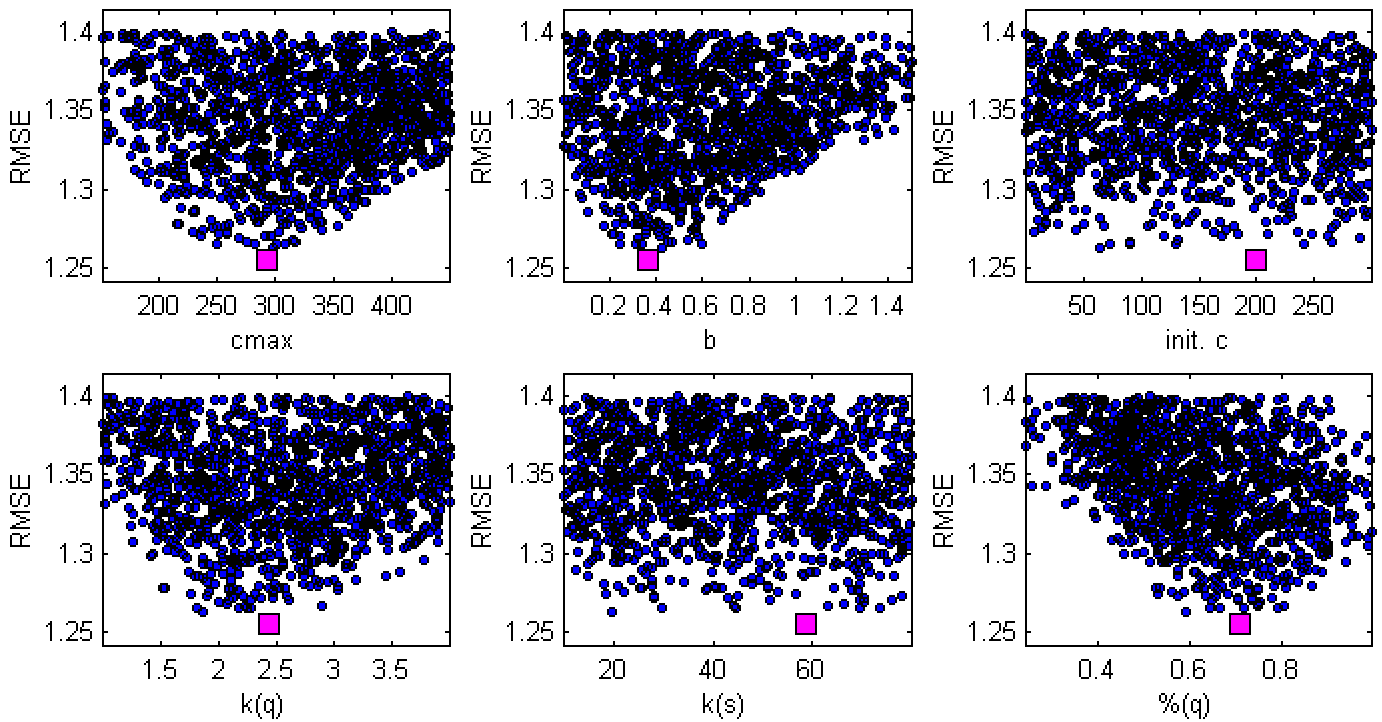
Peristerona: Volumetric fit and flow duration curve for the BUC with 2PAR RRMT mode structure.

Figure 10



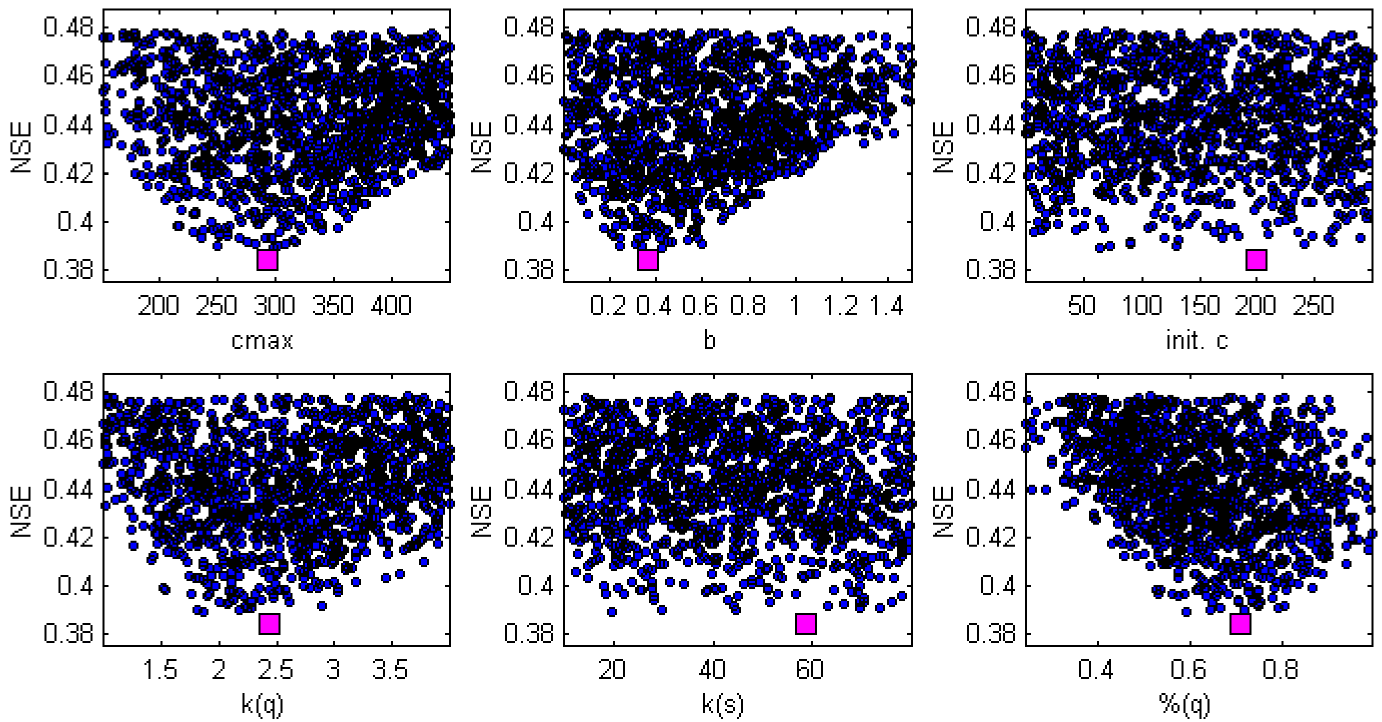
Peristerona: Dotty plot – PD4 2PAR model structure with RMSE_SQRT objective function.

Figure 11



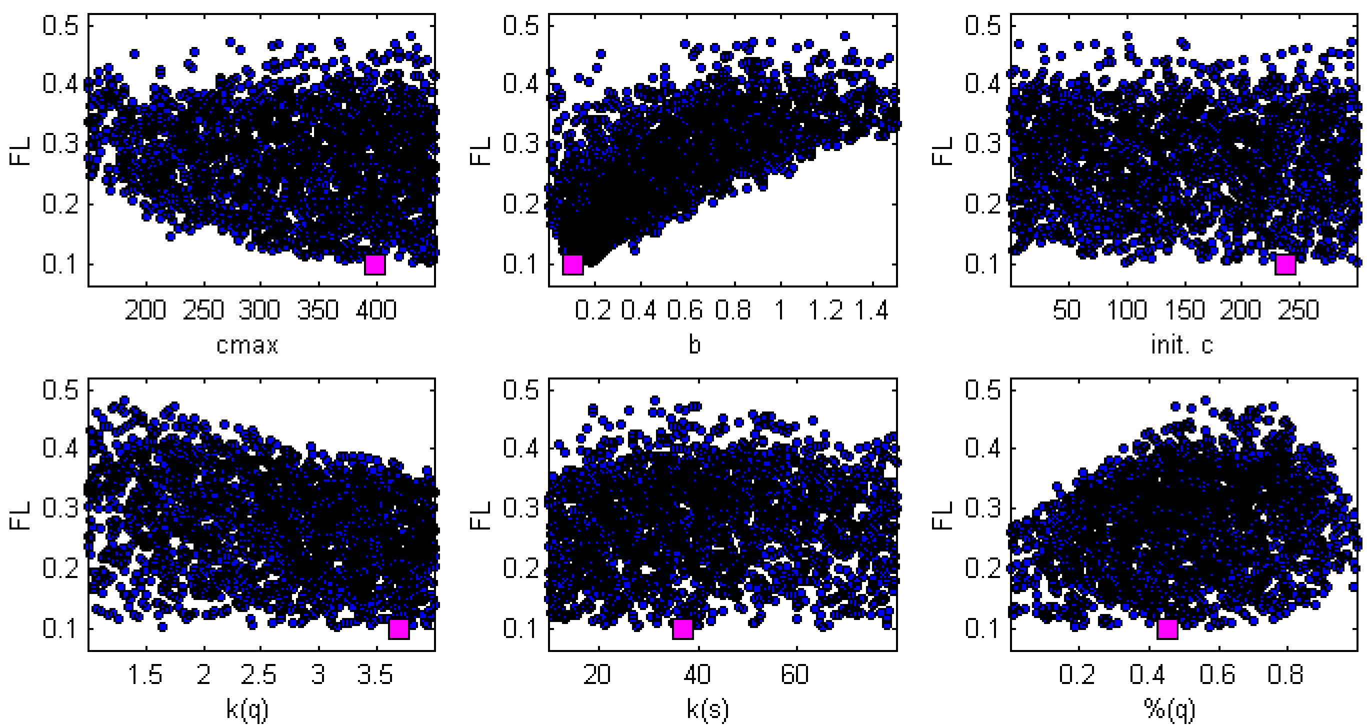
Peristerona: Dotty plot – PD4 2PAR model structure with RMSE objective function.

Figure 12



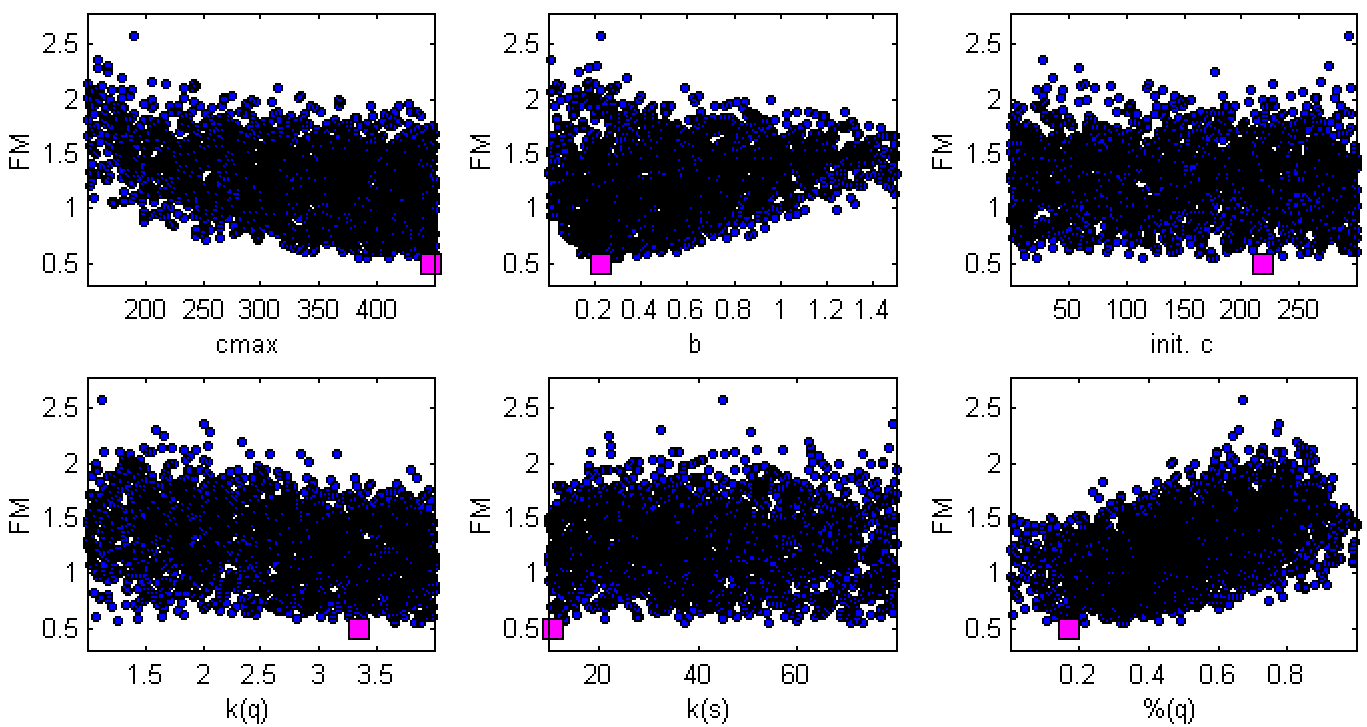
Peristerona: Dotty plot – PD4 2PAR model structure with NSE objective function.

Figure 13



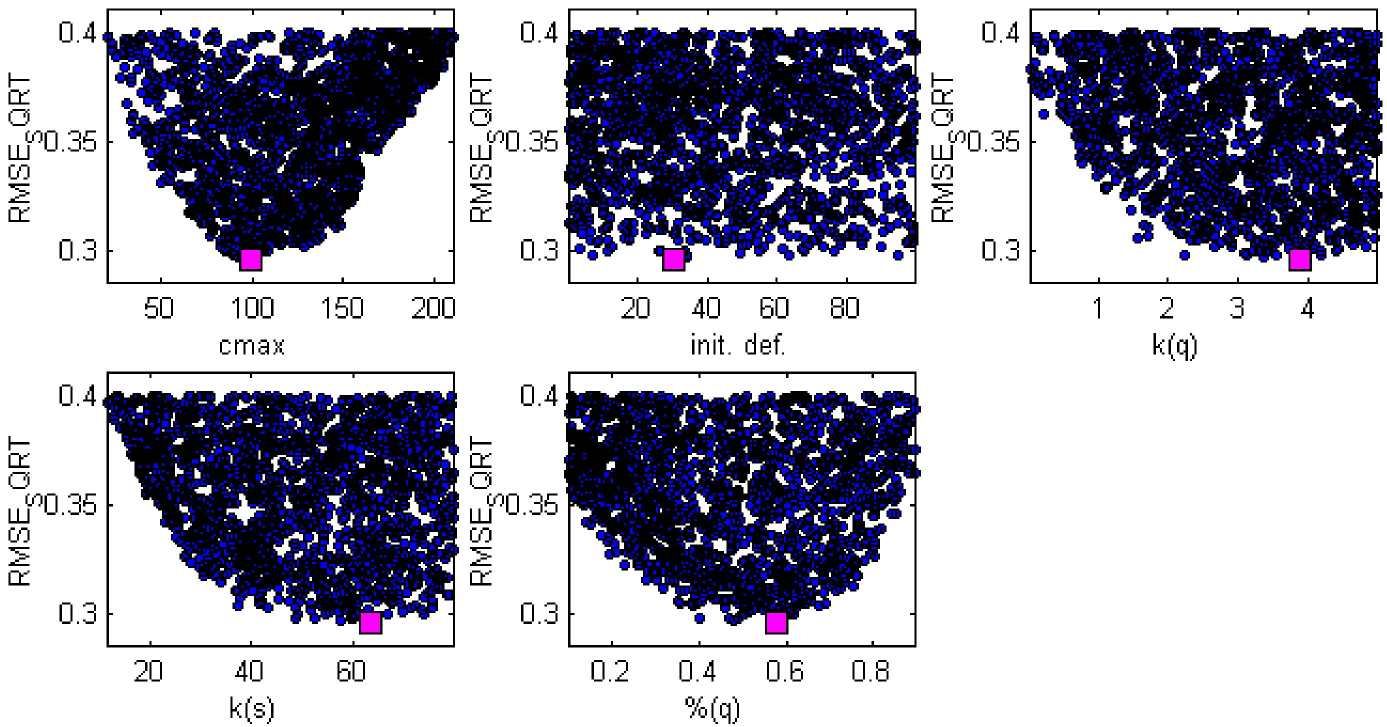
Peristerona: Dotty plot – PD4 2PAR model structure with FL objective function.

Figure 14



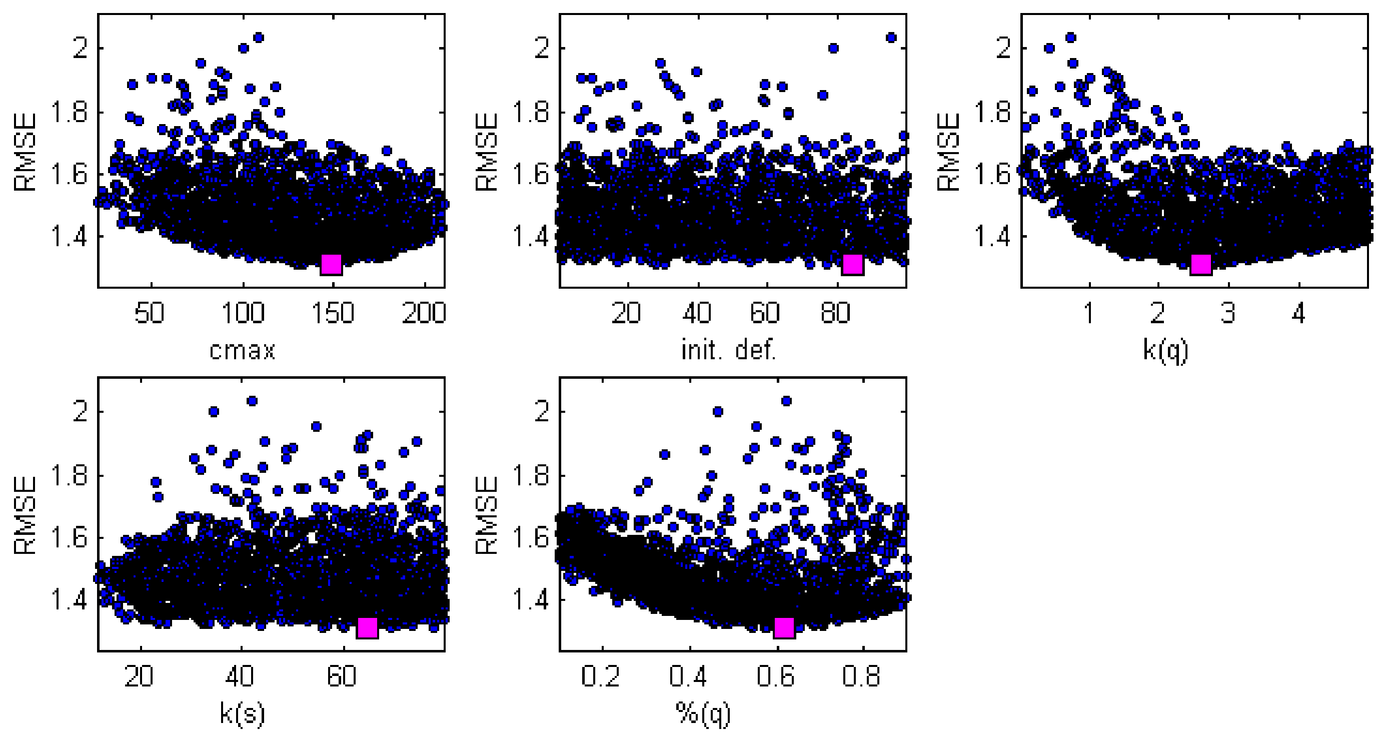
Peristerona: Dotty plot – PD4 2PAR model structure with FM objective function.

Figure 15



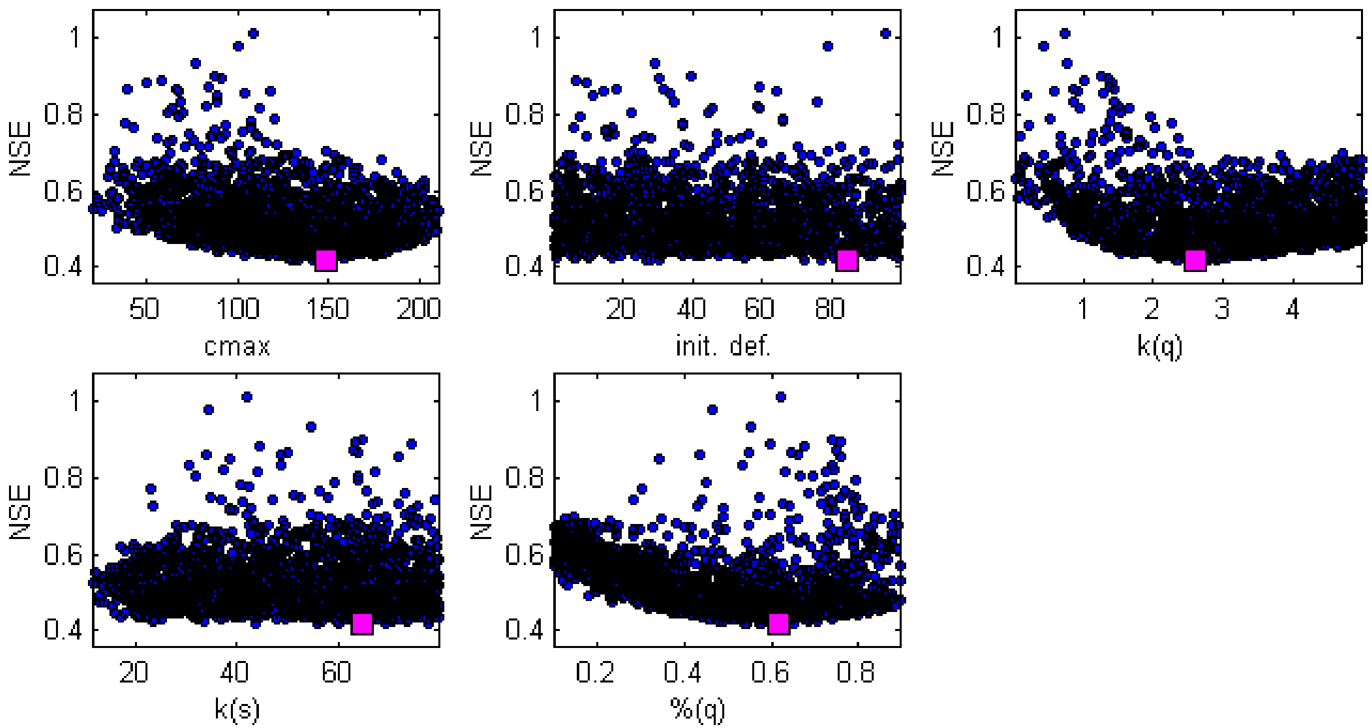
Peristerona: Dotty plot – BUC 2PAR model structure with RMSE_SQRT objective function.

Figure 16



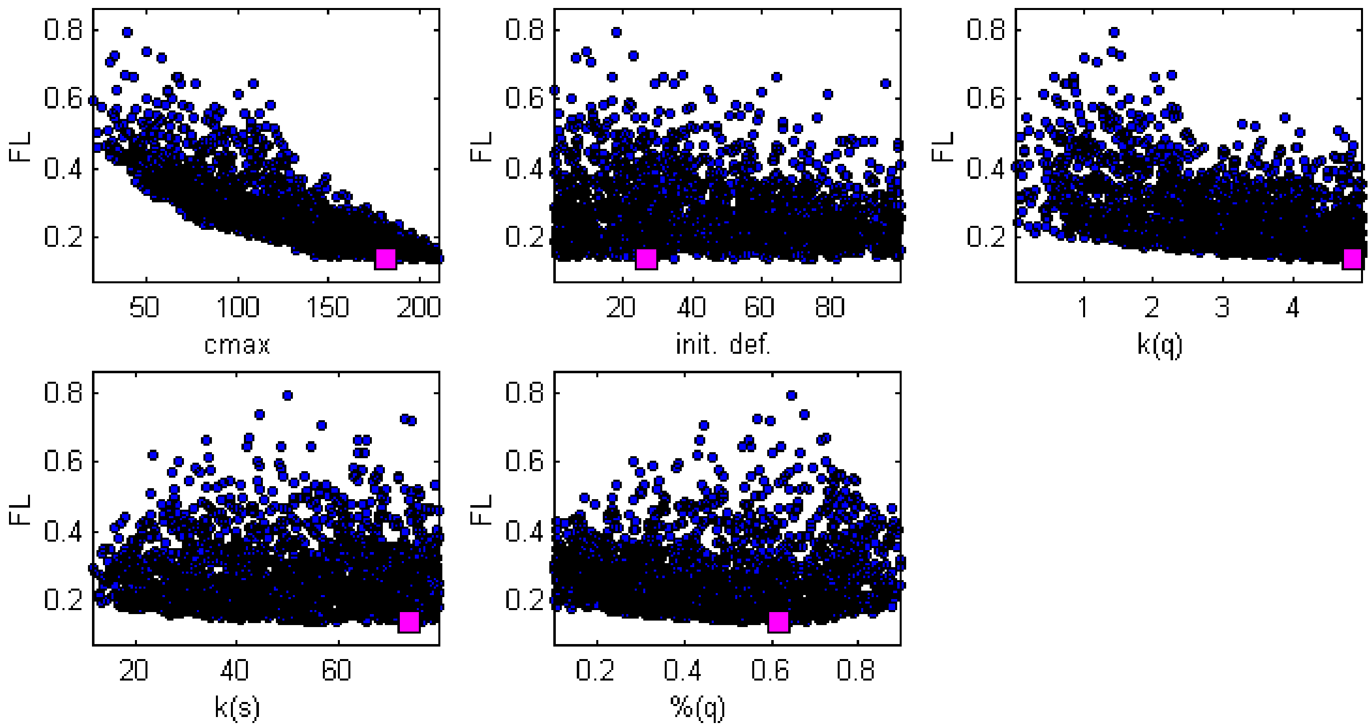
Peristerona: Dotty plot – BUC 2PAR model structure with RMSE objective function.

Figure 17



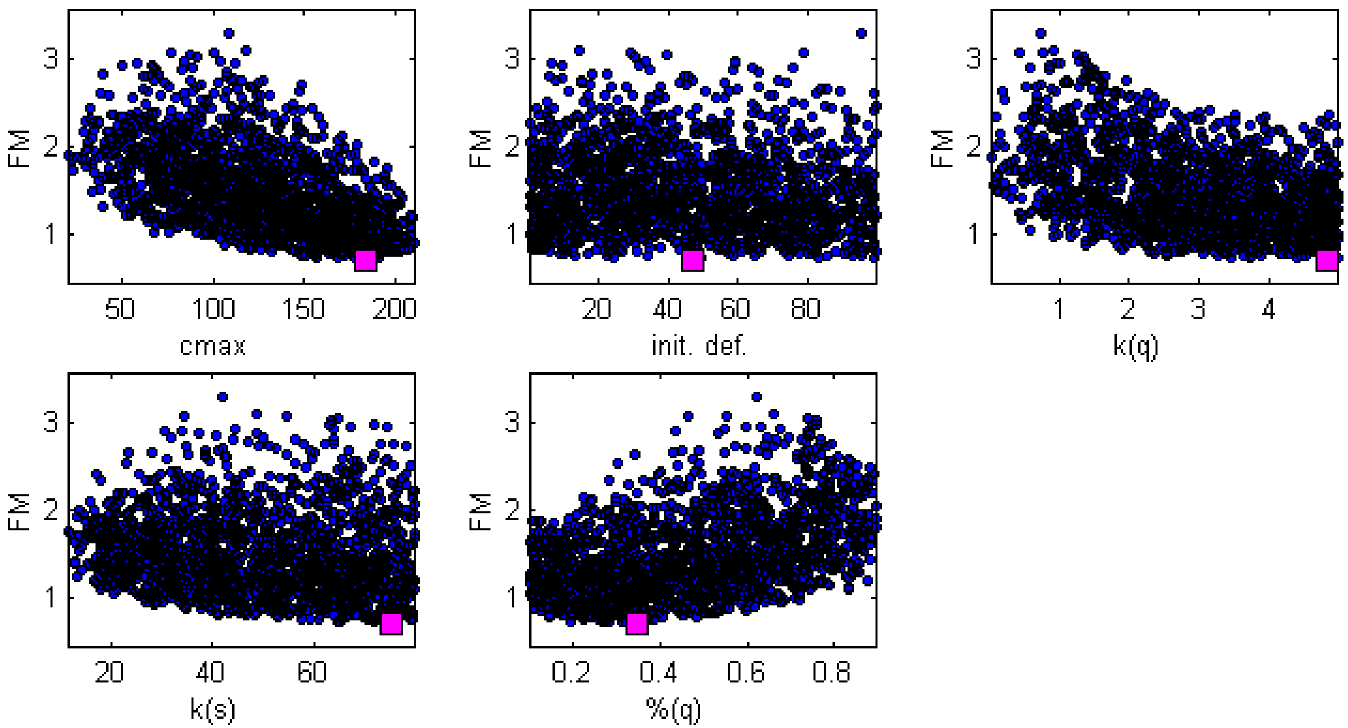
Peristerona: Dotty plot – BUC 2PAR model structure with NSE objective function.

Figure 18



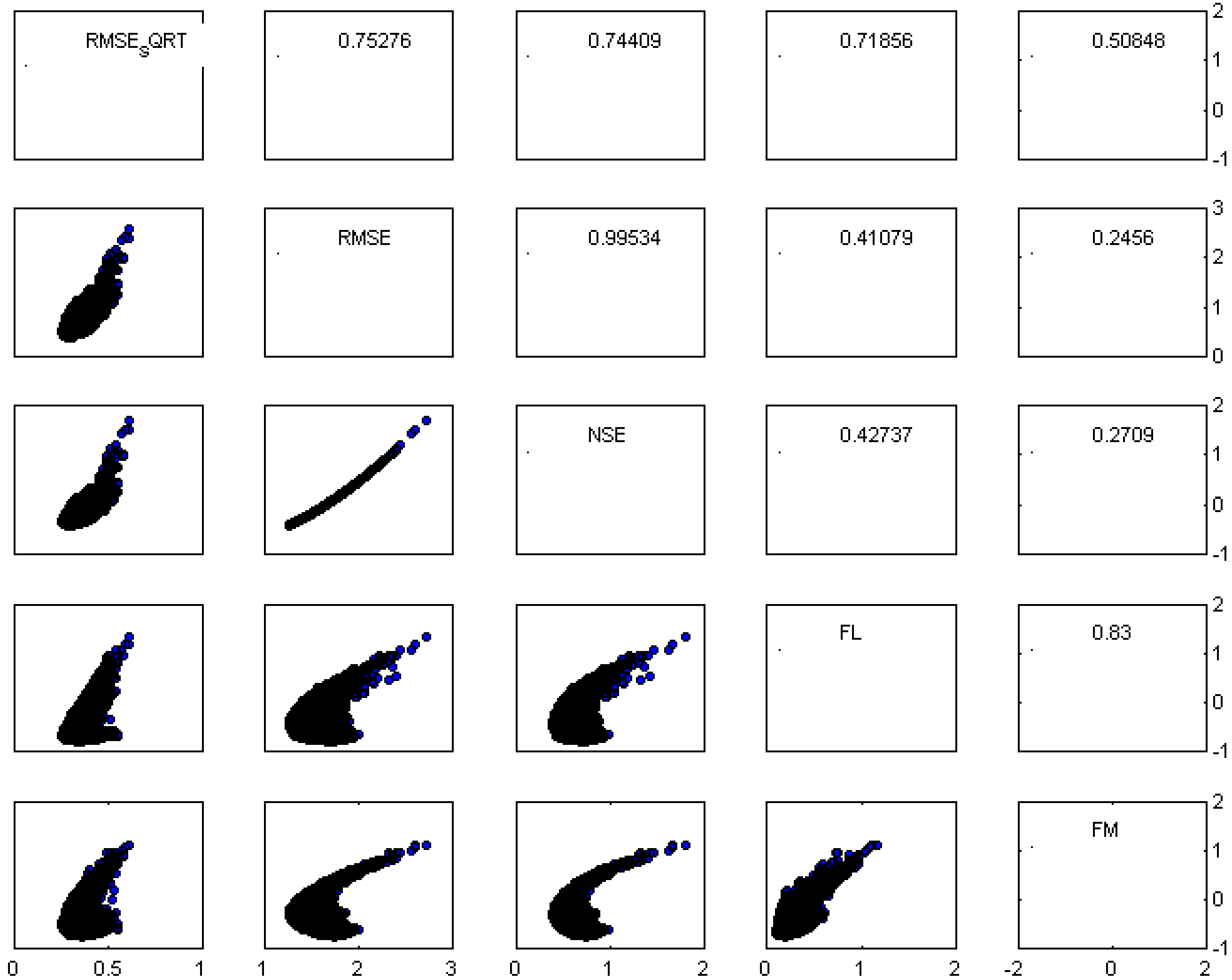
Peristerona: Dotty plot – BUC 2PAR model structure with FL objective function.

Figure 19



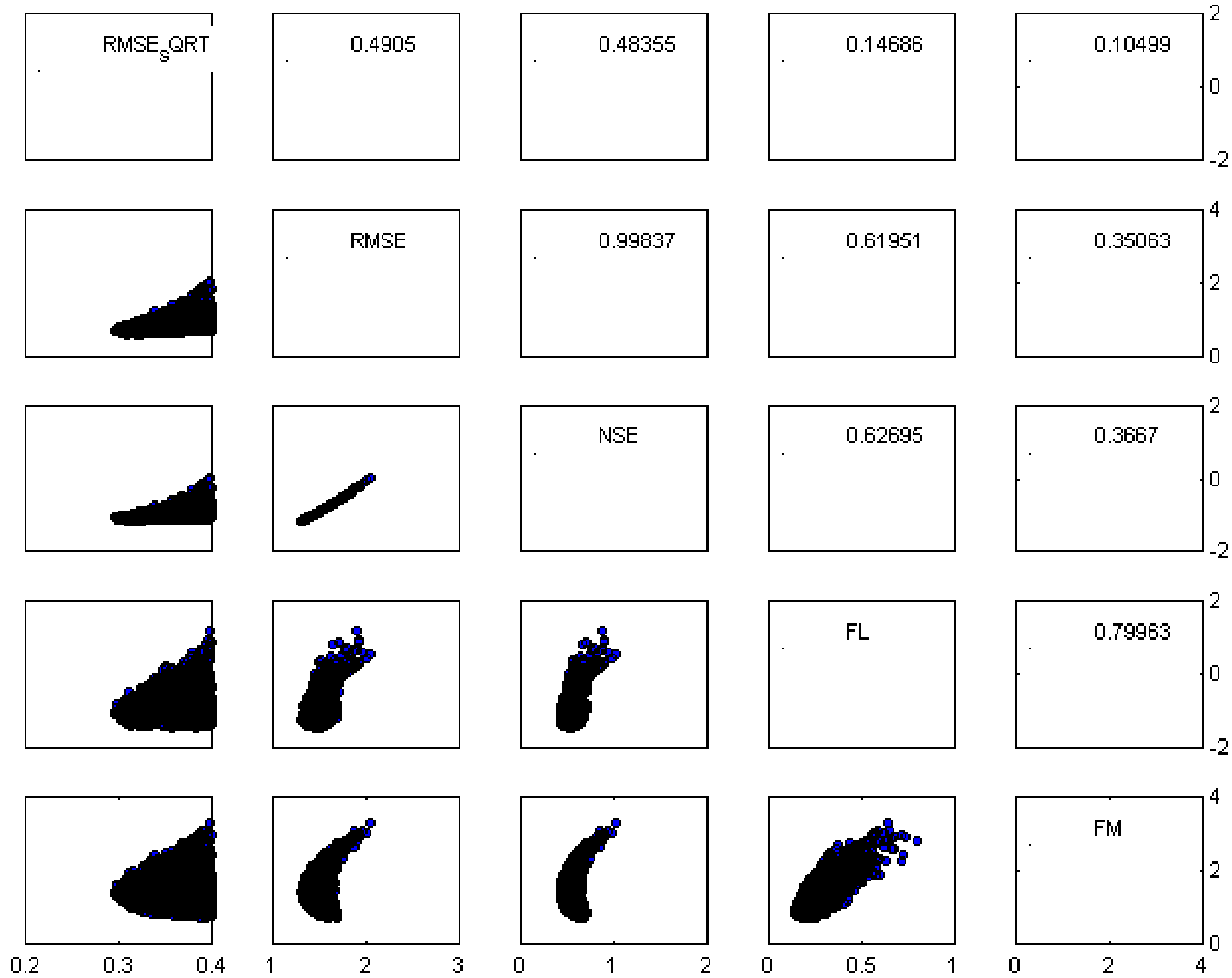
Peristerona: Dotty plot – BUC 2PAR model structure with FM objective function.

Figure 20



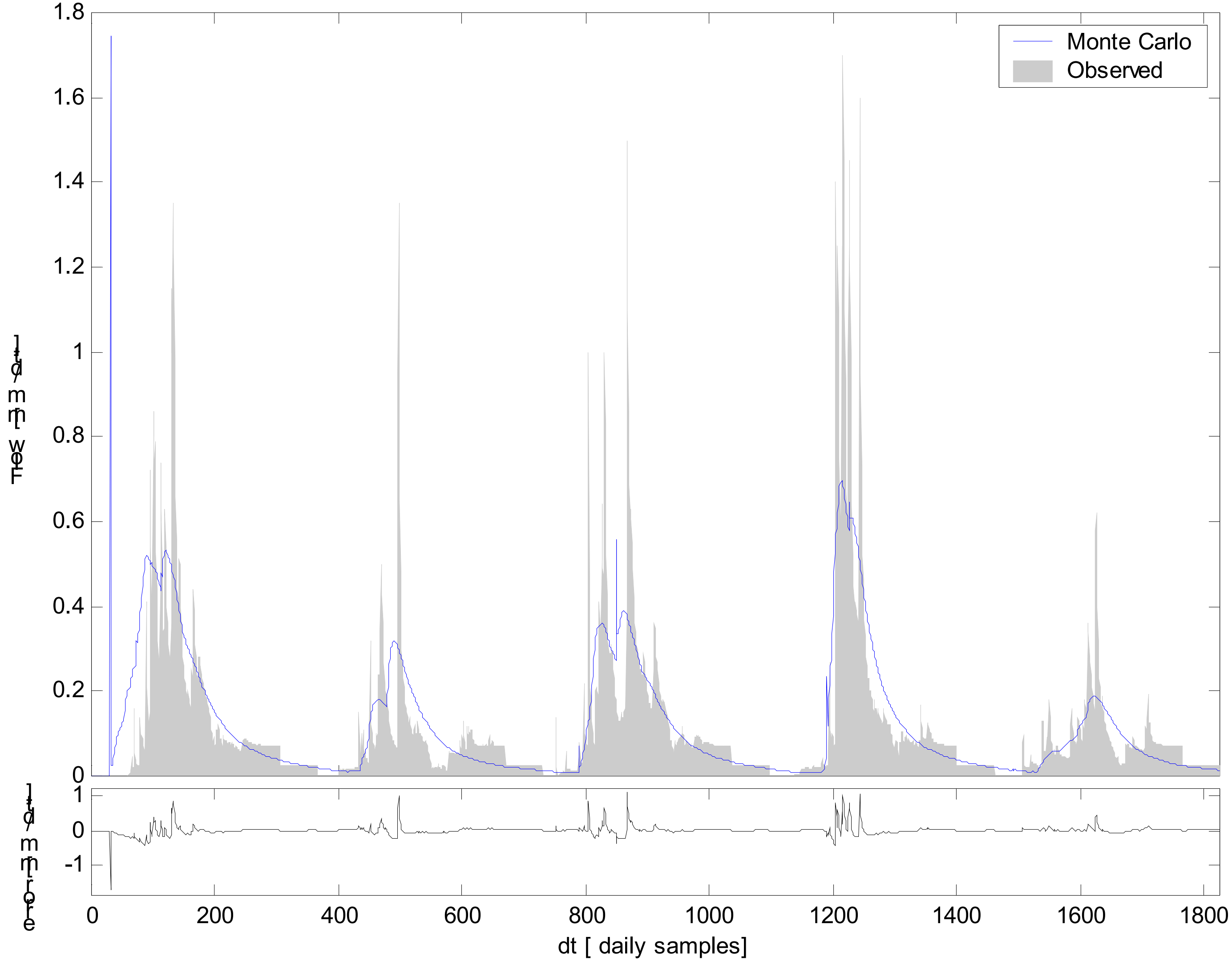
Peristerona: Multi objective plot for the PD4 2PAR model structure. Numerical values in boxes are values for correlation between different objective functions used. The diagonal boxes label the objective functions.

Figure 21



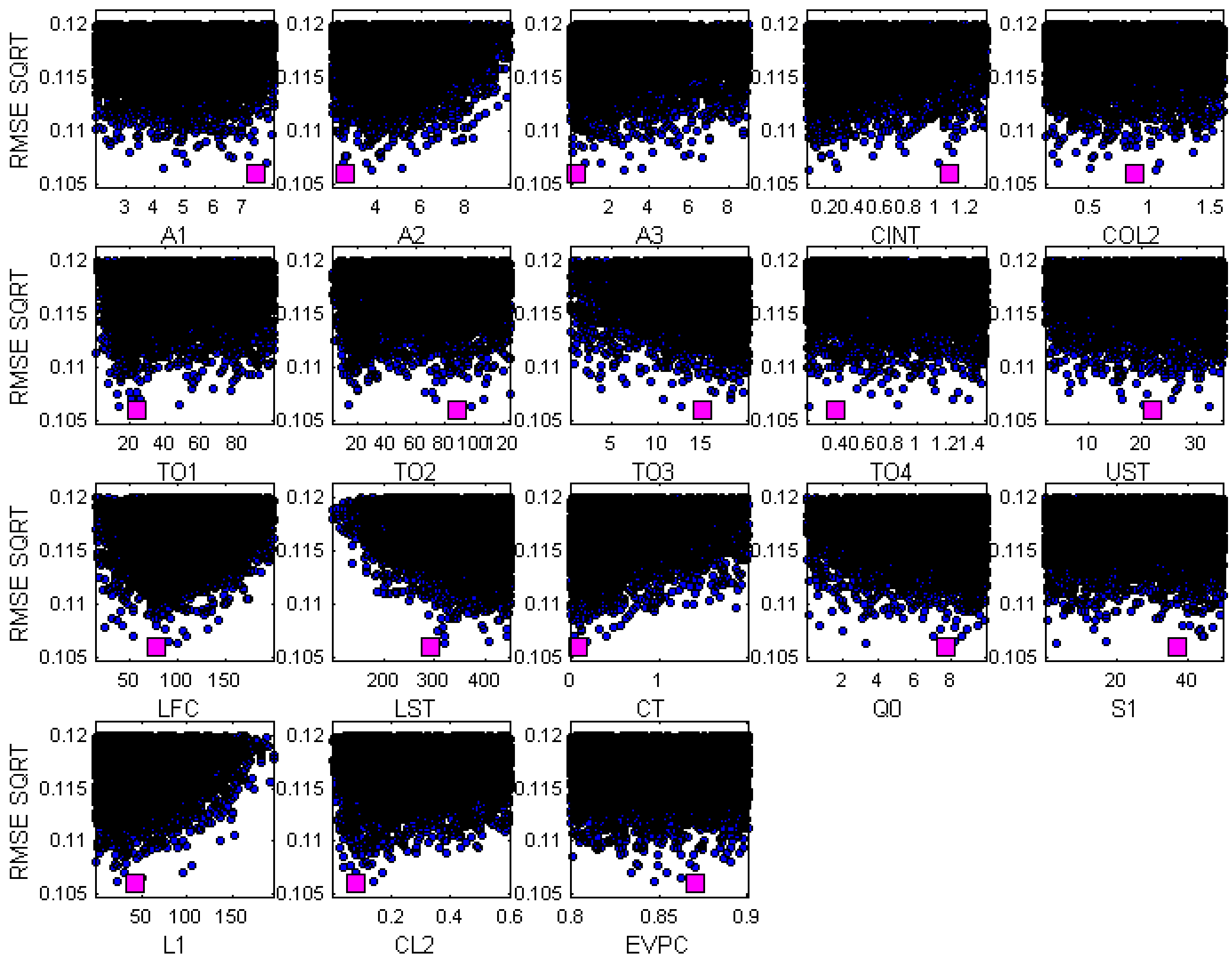
Peristerona: Multi objective plot for the BUC 2PAR model structure. Numerical values in boxes are values for correlation between different objective functions used. The diagonal boxes label the objective functions.

Figure 22



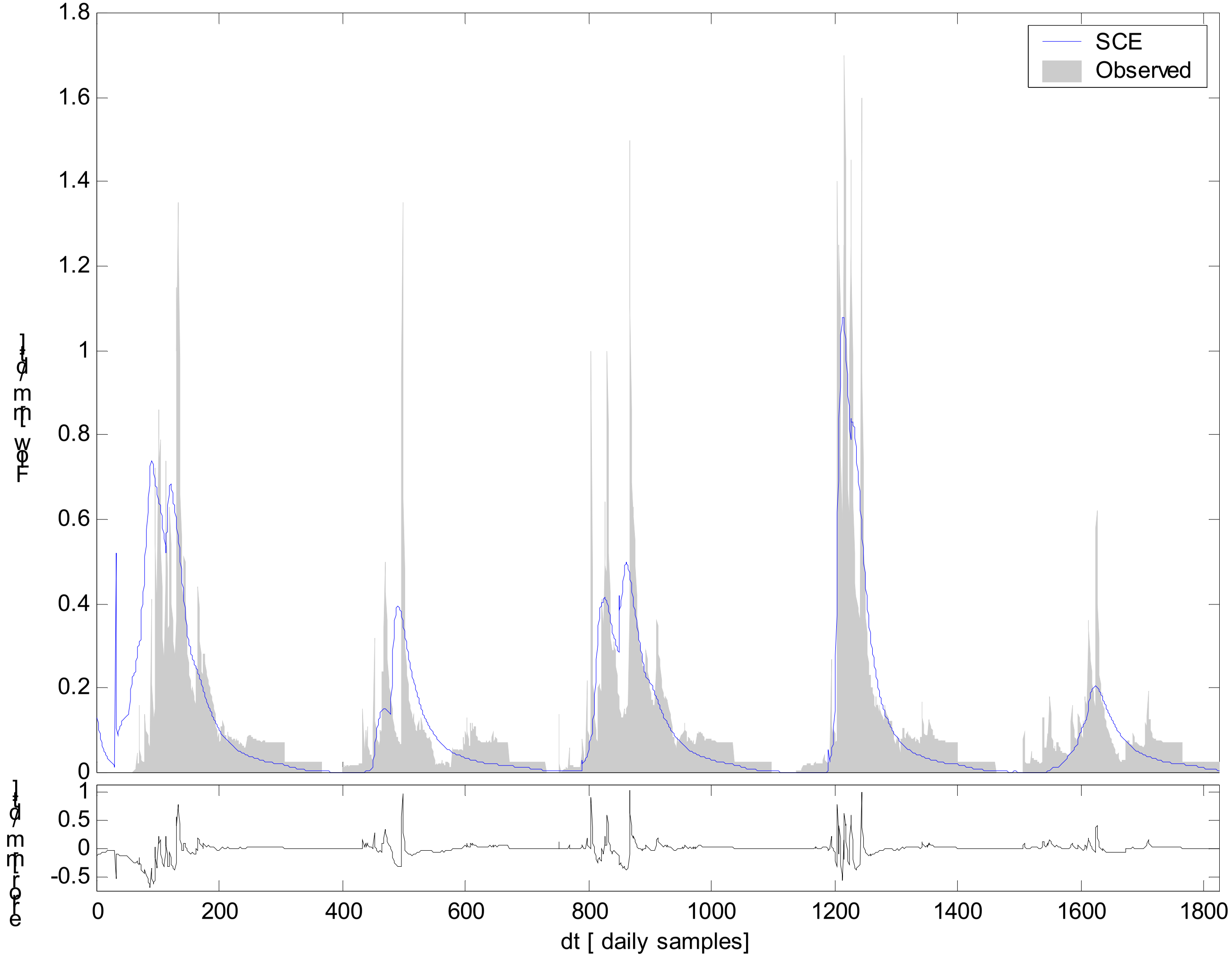
Flow simulated by the Mero model using parameters obtained using Montecarlo simulation. The first 5% of time series was used as a warm up period and so does not affect the objective function calculations.

Figure 23



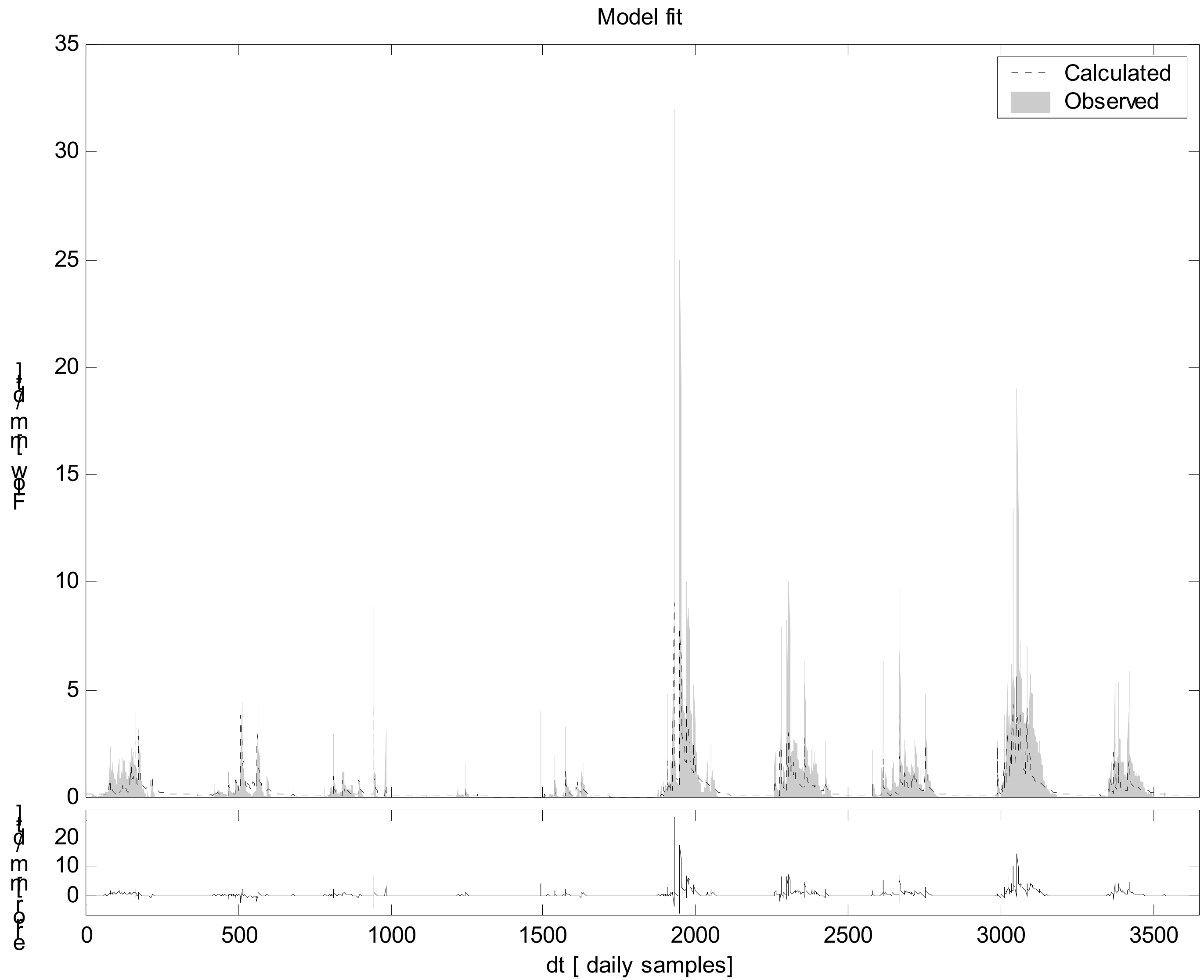
Dotty plots for Monte Carlo generated parameter sets used by the Mero model. For parameter definitions see Panaretou, 1990.

Figure 24



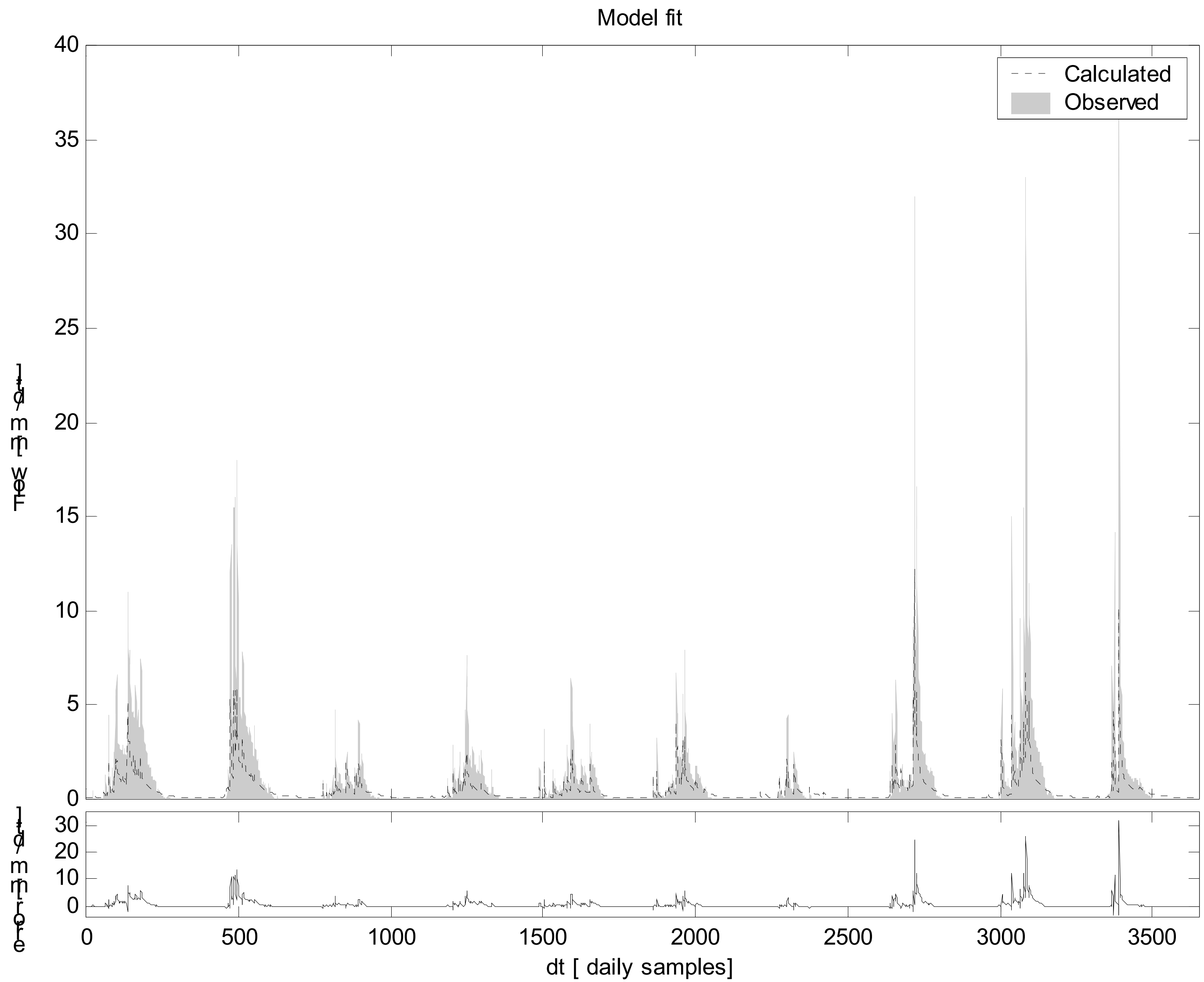
Flow simulated by the Mero model using parameters obtained using the Shuffle Complex Evolution (SCE) algorithm.

Figure 25



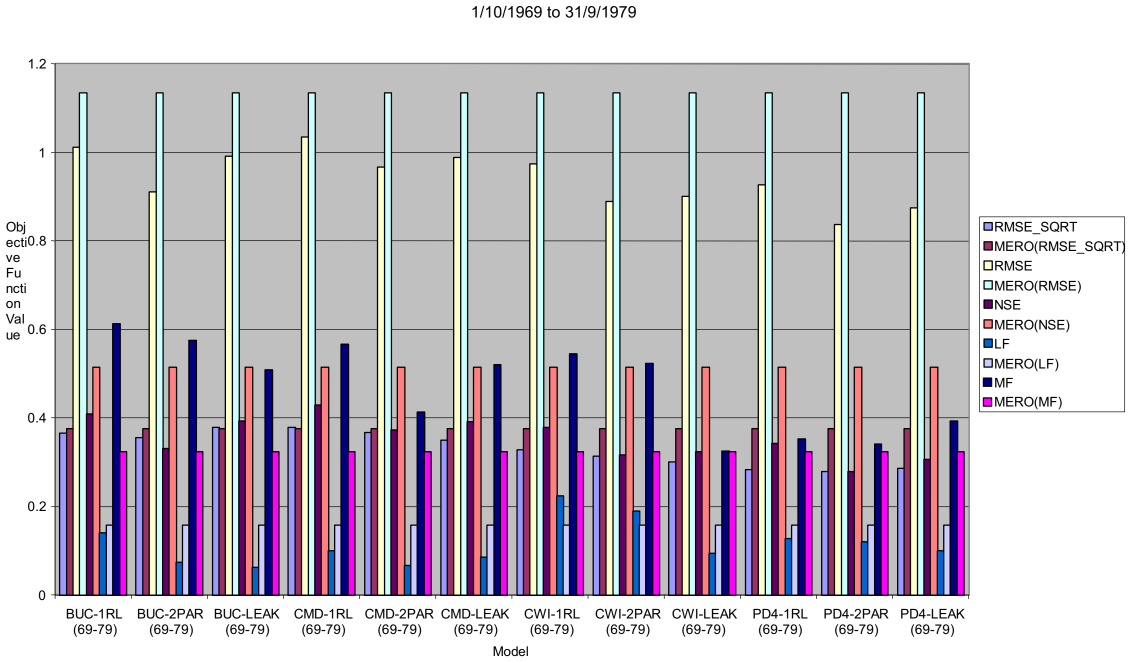
Dhiarizos: Mero Model fit for the period 1/10/69 to 31/9/79.

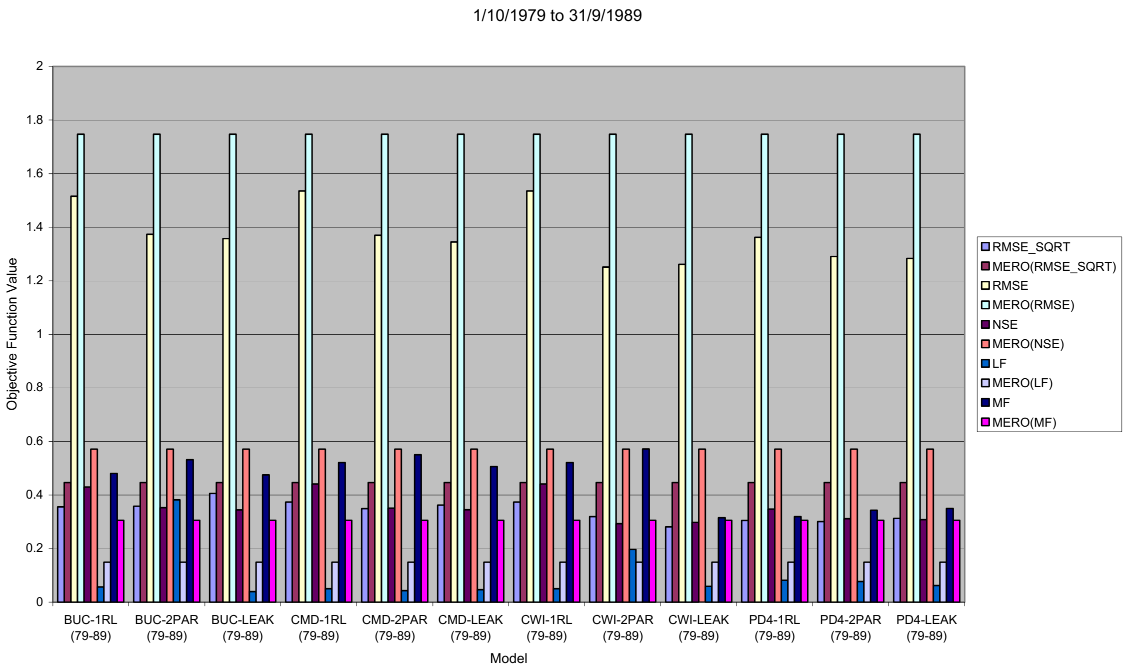
Figure 26



Dhiarizos: Mero Model fit for the period 1/10/79 to 31/9/89.

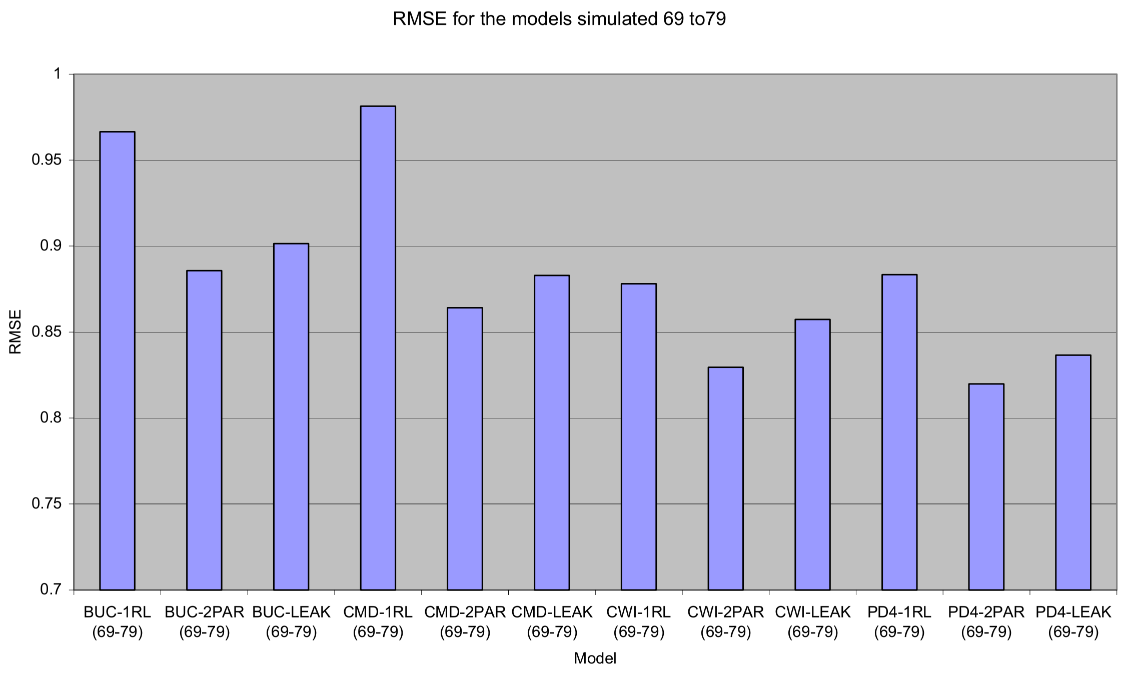
Figure 27





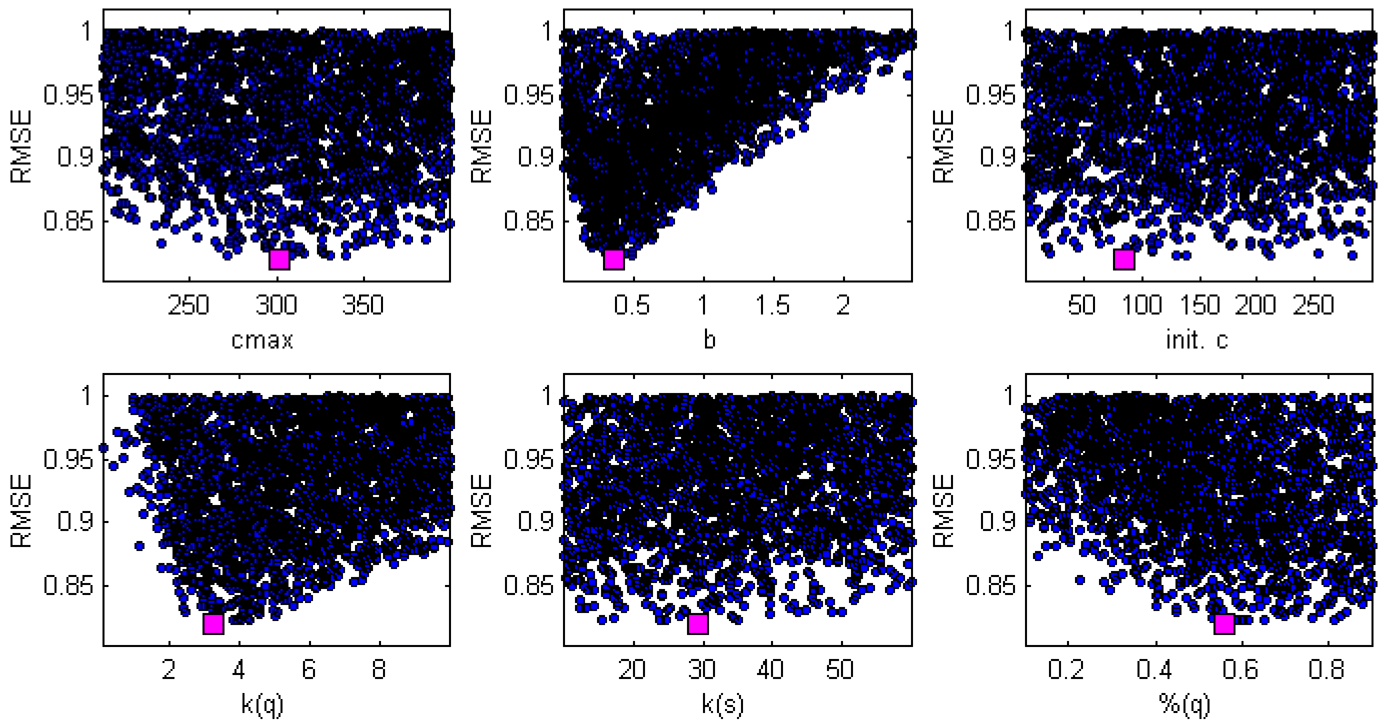
Dhiarizos: Objective function values obtained by the RRMT and Mero models for the periods 69 to79 and 79 to 89. The model parameters are those in Table 2.

Figure 28



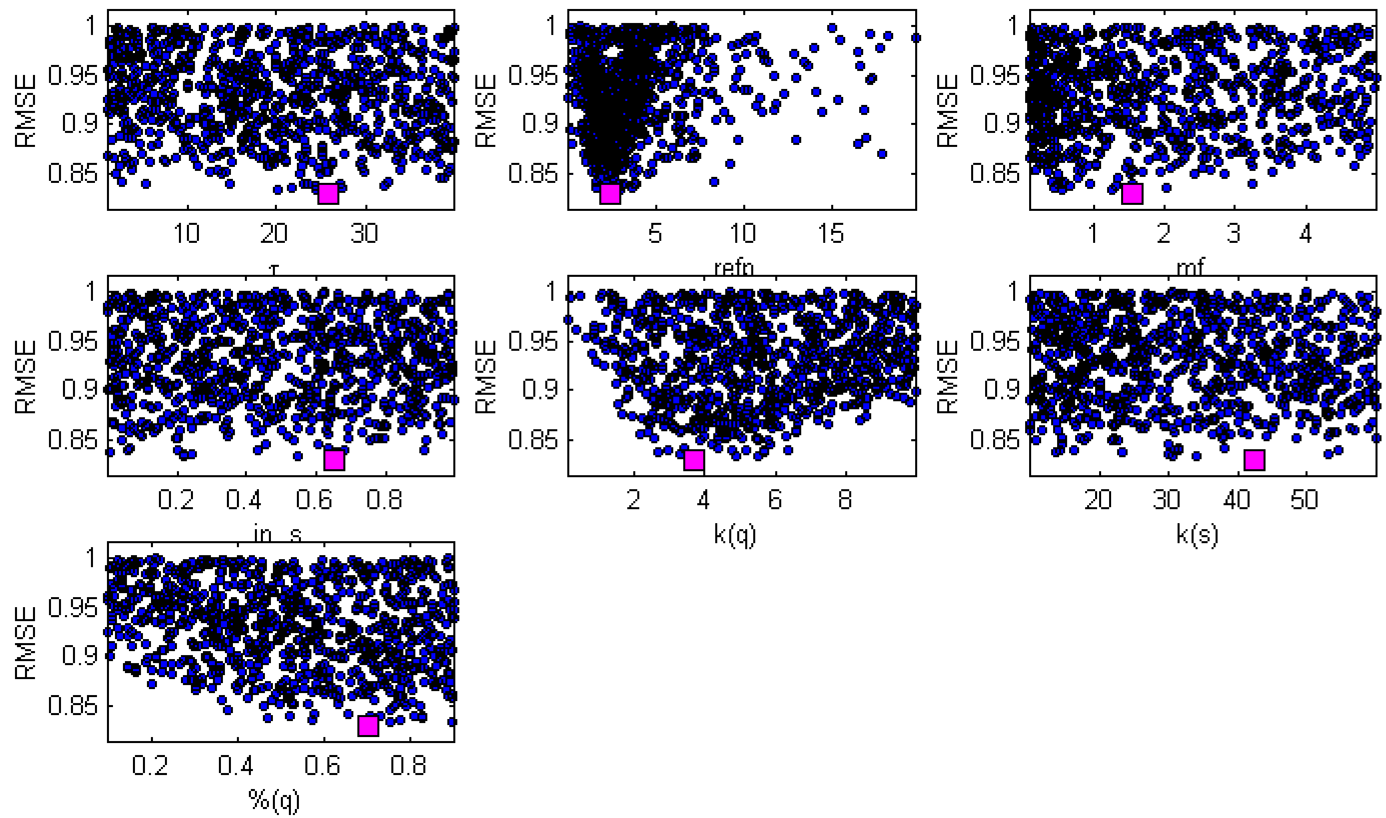
Dhiarizos: Optimum RMSE values for the different RRMT model structure simulations (1969 to 1979).

Figure 29



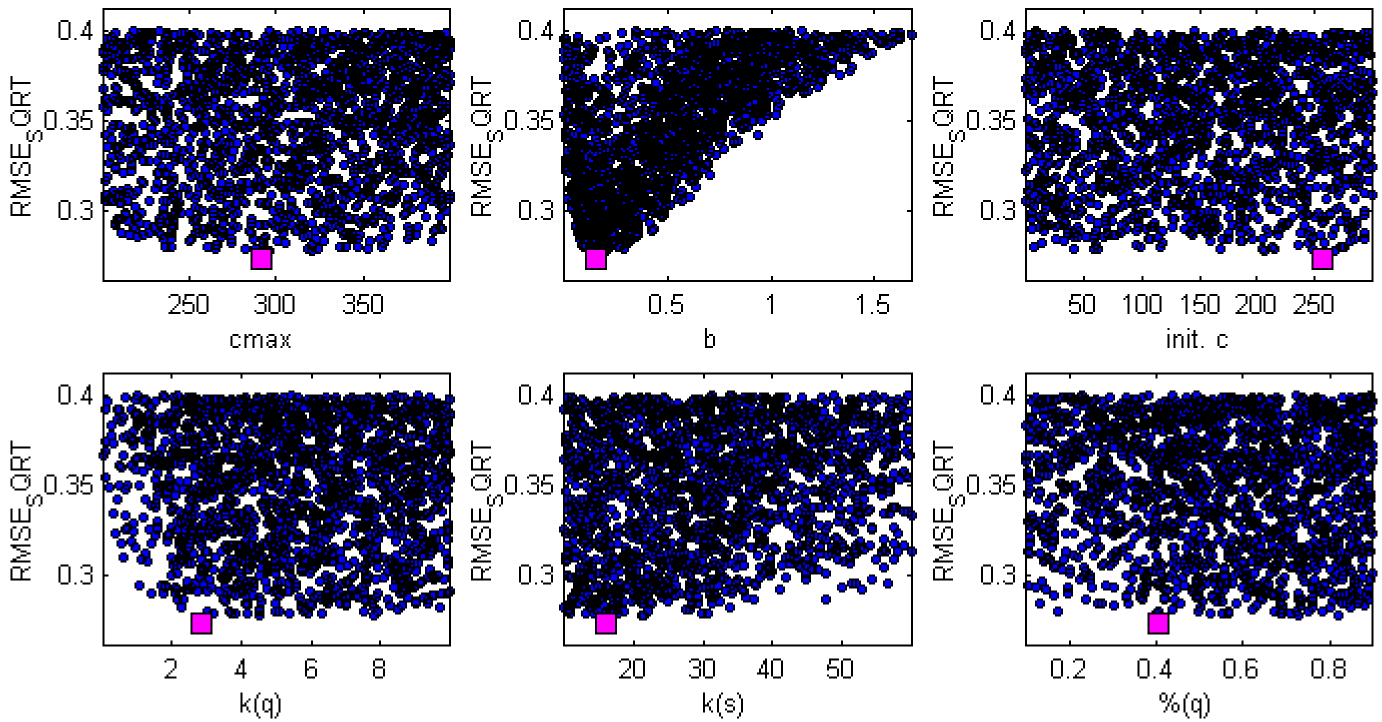
.Dhiarizos (69 to79): Dotty plots - PD4-2PAR model with RMSE objective function. Optimum value is 0.8198.

Figure 30



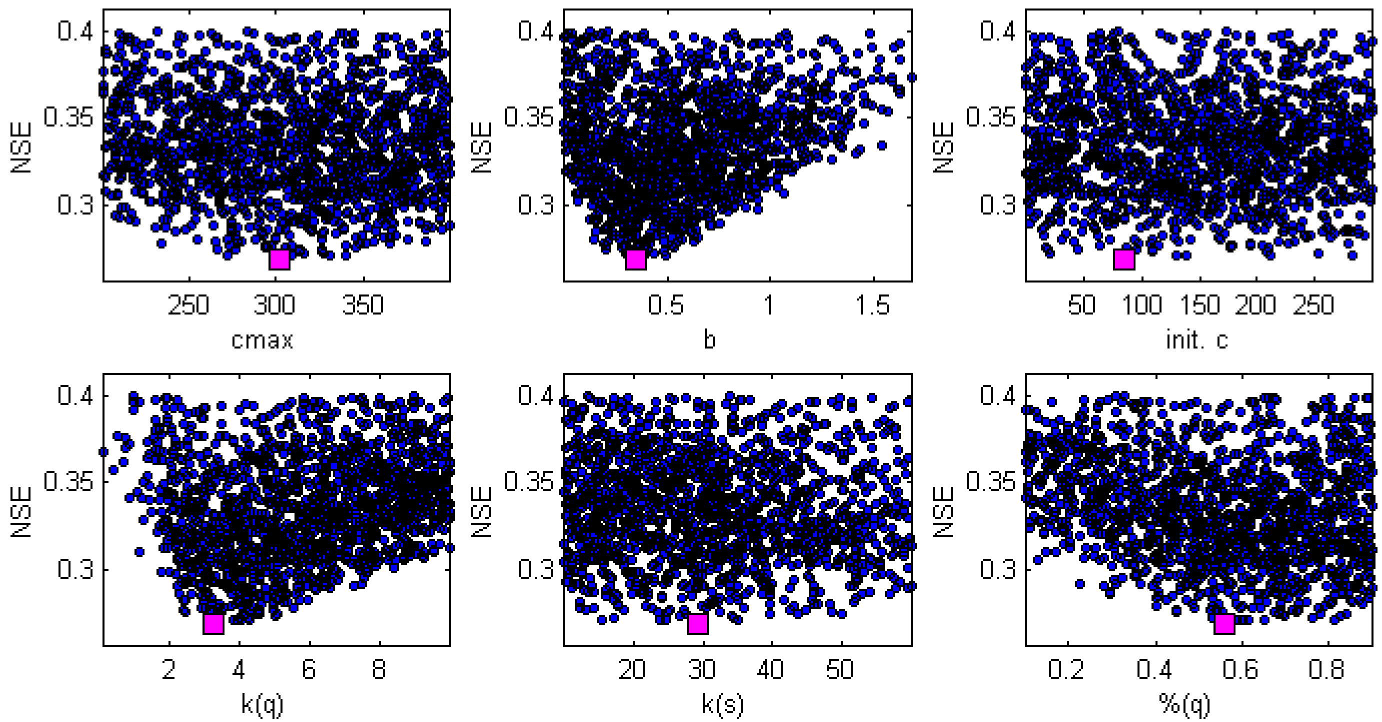
Dhiarizos (69 to79): Dotty plots - CWI-2PAR model with RMSE objective function. Optimum value is 0.8295.

Figure 31



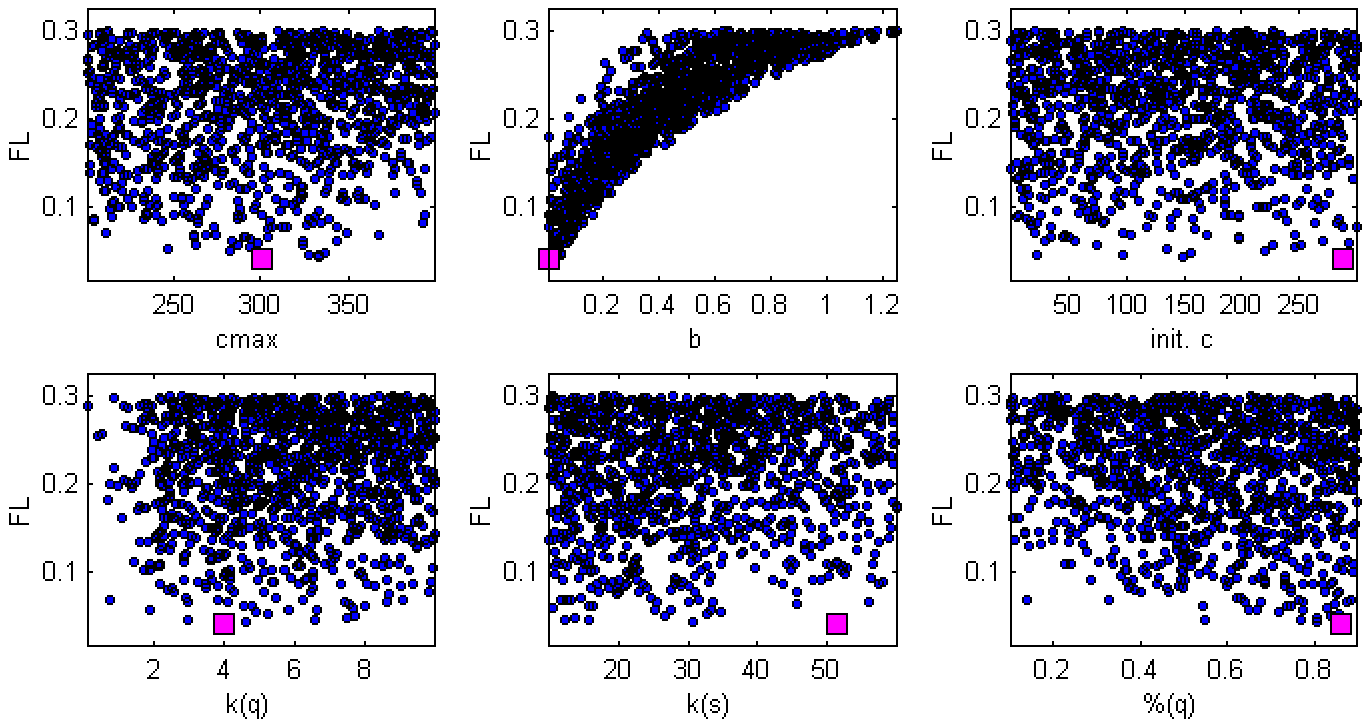
Dhiarizos (69 to79): Dotty plots - PD4-2PAR model with RMSE_SQRT objective function.

Figure 32



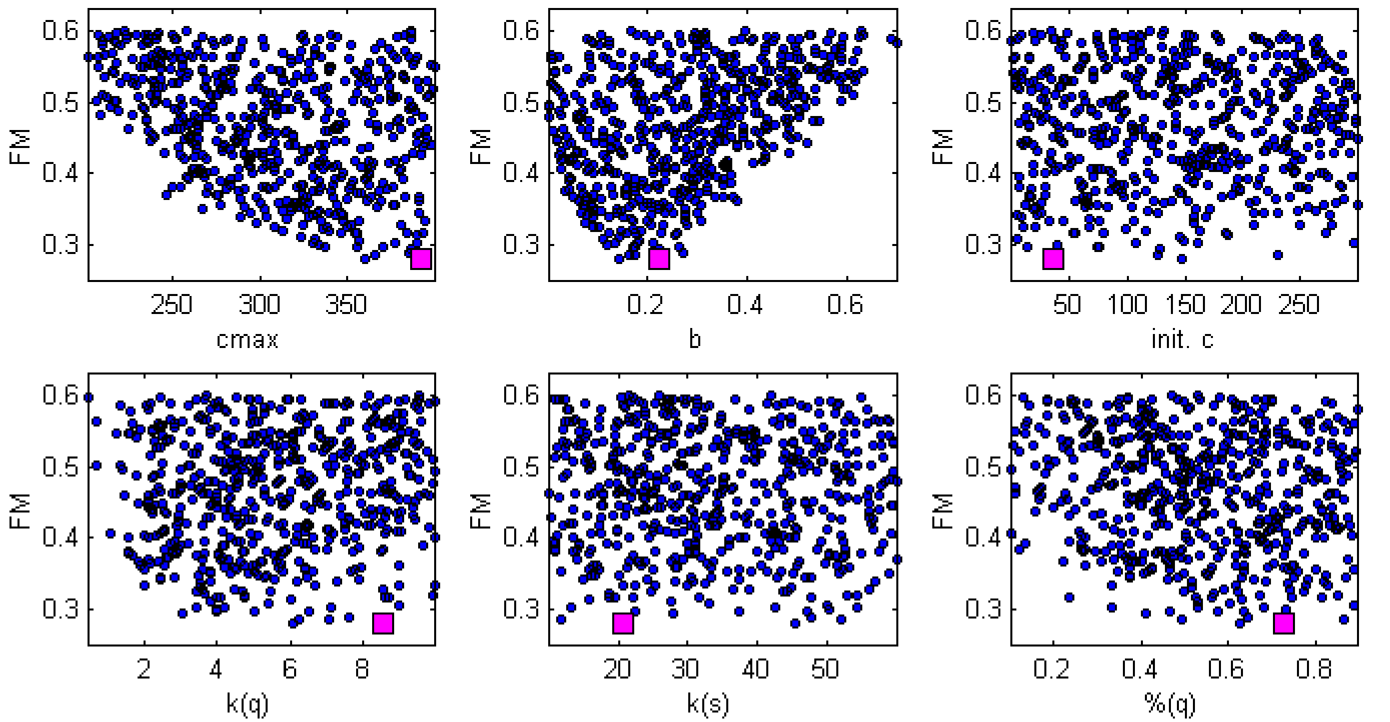
Dhairizos (69 to 79): Dotty plots - PD4-2PAR model with NSE* objective function.

Figure 33



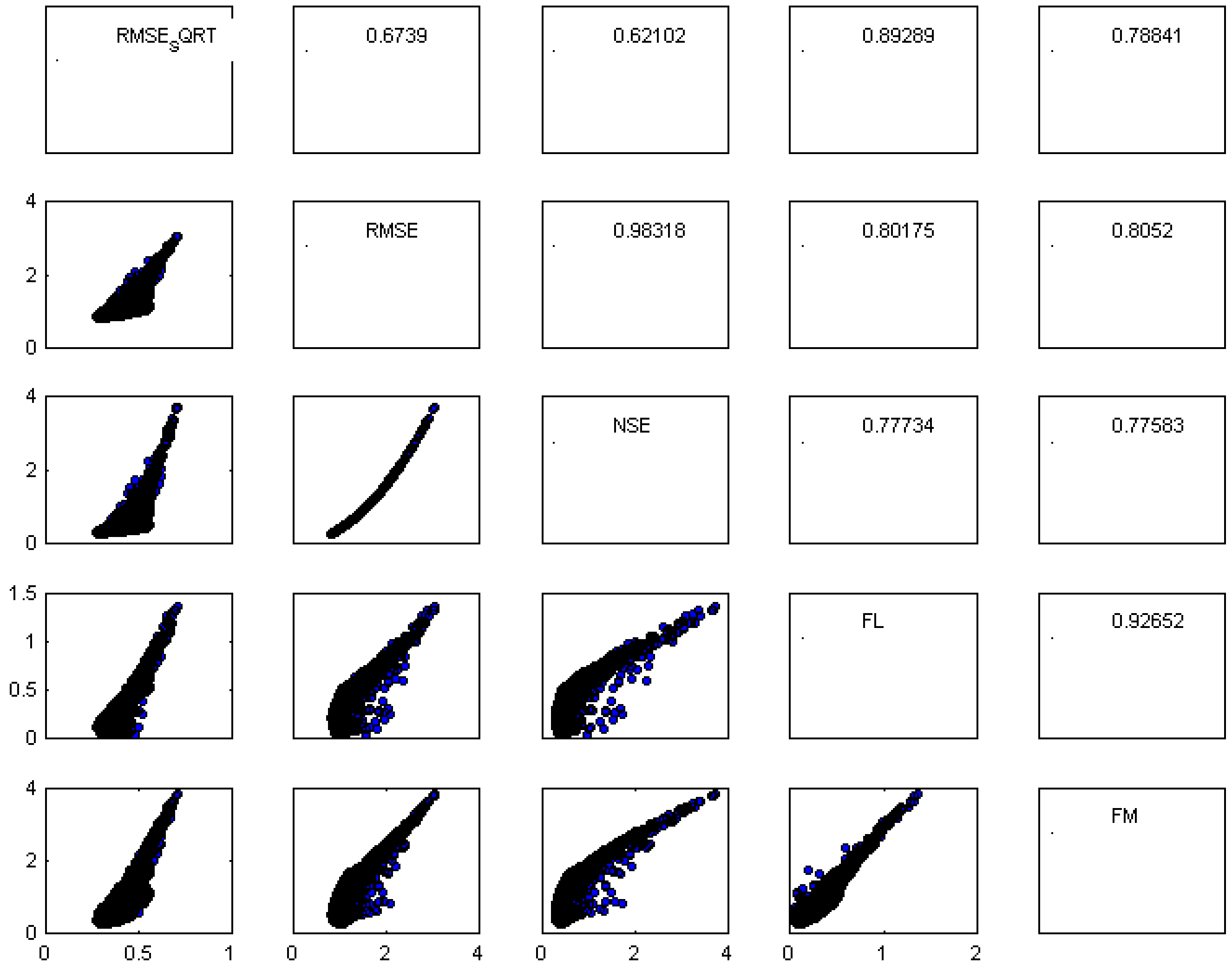
Dhairizos (69 to 79): Dotty plots - PD4-2PAR model with FL objective function.

Figure 34



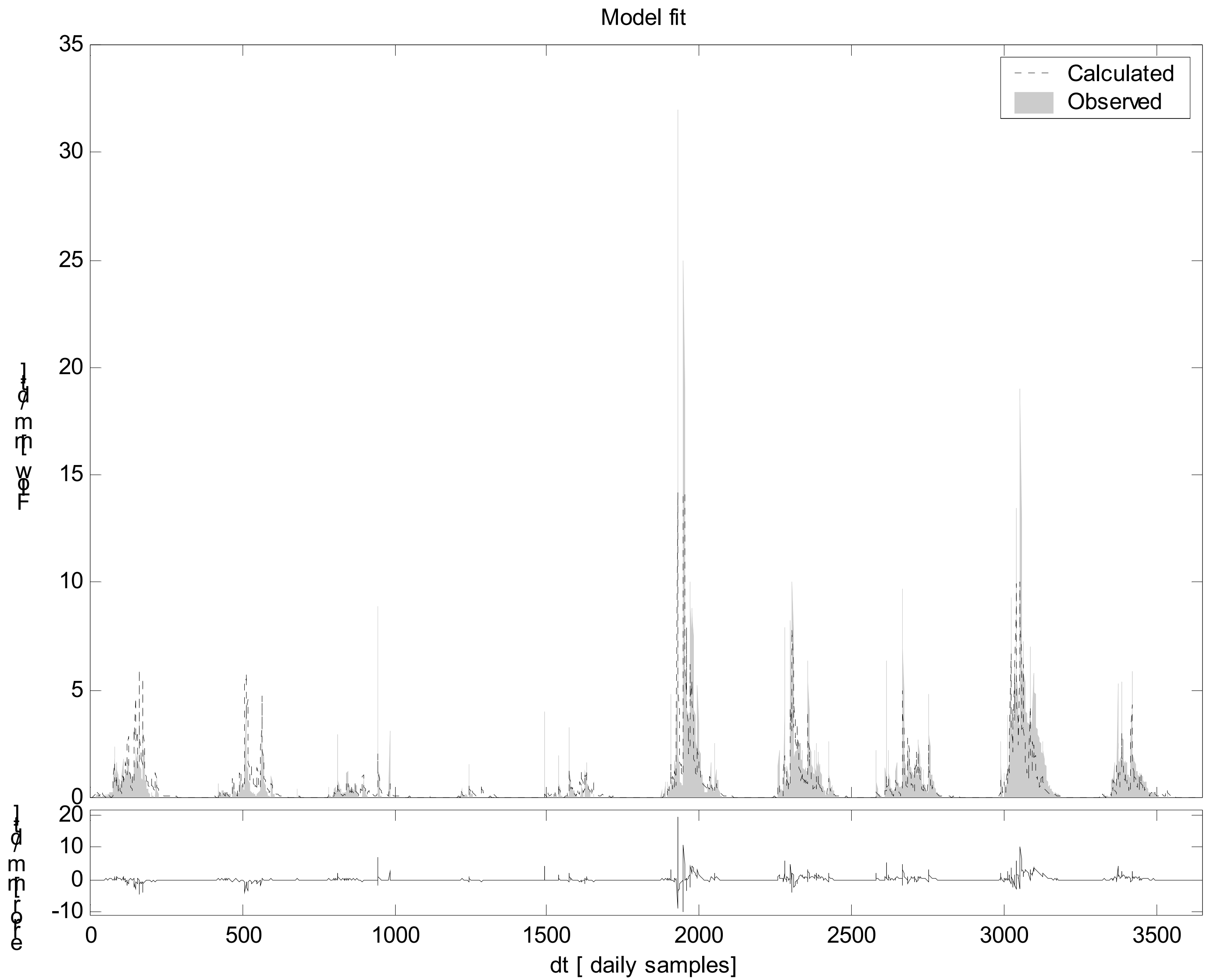
Dhairizos (69 to 79): Dotty plots - PD4-2PAR model with FM objective function.

Figure 35



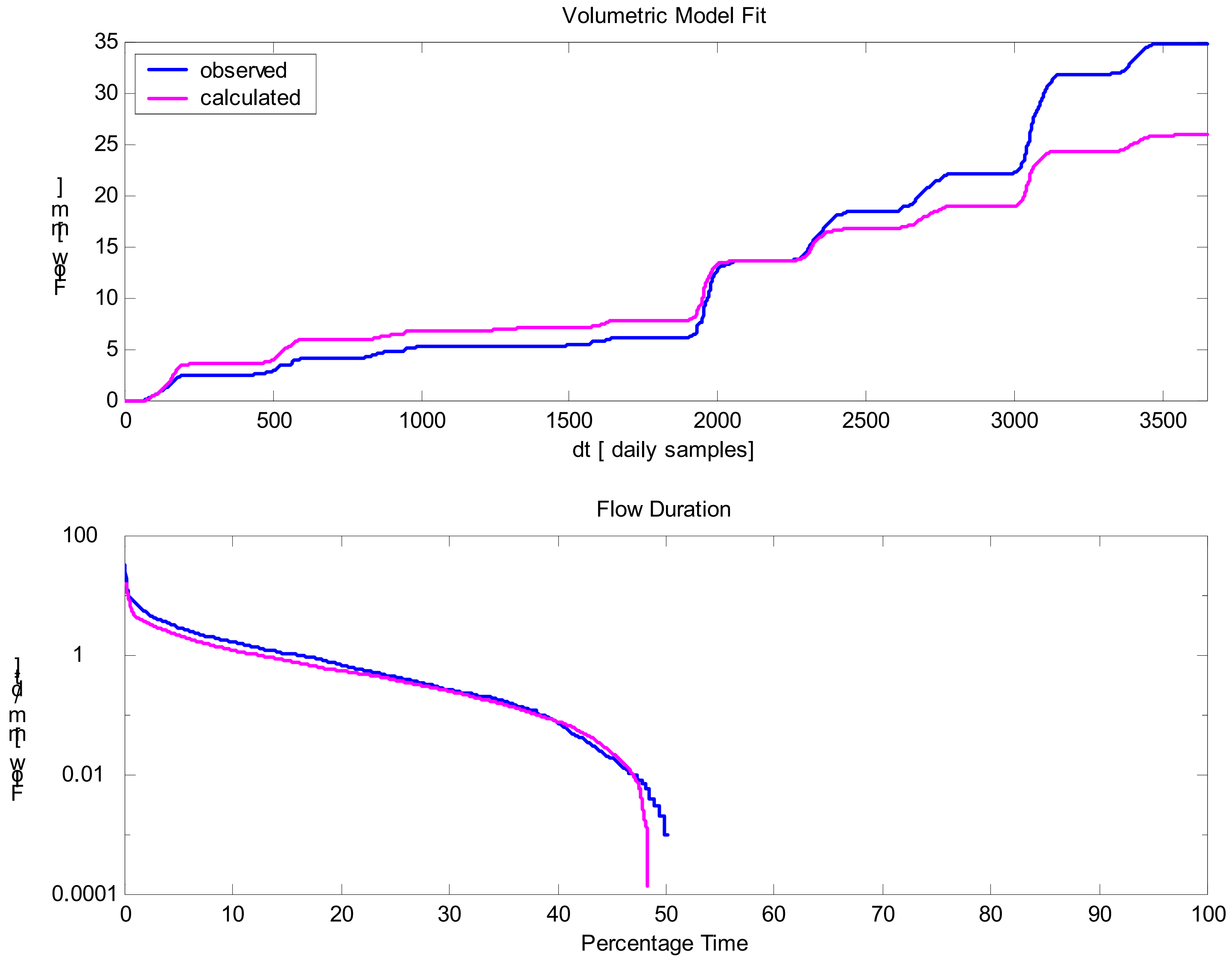
Dhaiarizos (69 to 79): Multi objective plot for the PD4 2PAR model structure. Numerical values in boxes are values for correlation between different objective functions used. The diagonal boxes label the objective functions.

Figure 36



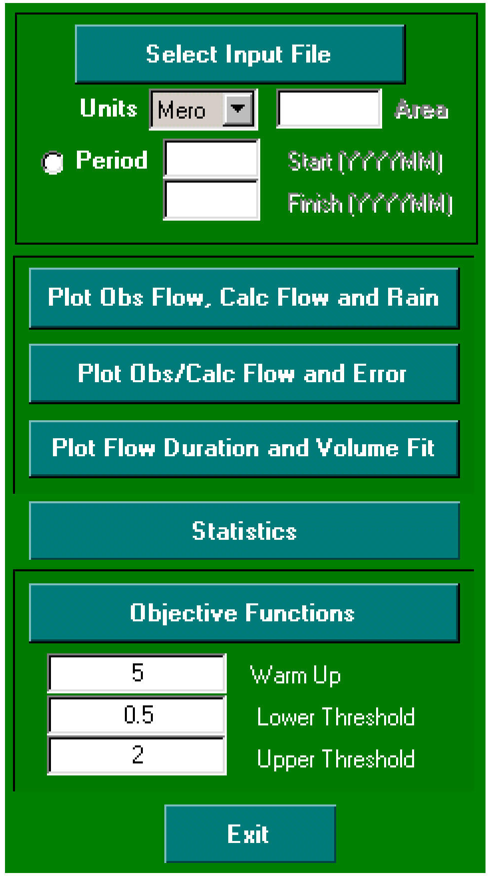
Dhiarizos: PD4 with 2PAR RRMT model structure calculated flow plotted against observed flow for the 1969-79 RRMT fitting period.

Figure 37



Dhiarizos (1969-79): Volumetric fit and flow duration curve for the PD4 with 2PAR RRMT mode structure.

Figure 38



Matlab interface for visualizing Mero model output.