CHAPTER 3

Regional Calibration of Watershed Models

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1. INTRODUCTION

As watershed models become increasingly sophisticated and useful, there is a need to extend their applicability to locations where they cannot be calibrated or validated. It is only natural that as watershed models, computer technology and hydrometeorologic data sources continue to evolve, there will be an ever increasing need to apply watershed models where streamflow data is unavailable for calibration. Without streamflow data, a watershed model cannot be calibrated or validated, hence regional methods are needed which relate easily measured watershed characteristics to watershed model parameters. The focus of this chapter is on a review of the various approaches which have been taken for estimating watershed model parameters in situations when streamflow data is unavailable for model calibration and validation.

In the past decade, there has been a significant increase in research relating to the regional calibration of watershed models to enable their use at ungauged sites. The increased importance of regional methods for estimating watershed model parameters is influenced by and related to the following emerging themes:

1.1 Regional Calibration is a Fundamental Hydrologic Challenge:

Transfer of hydrologic characteristics of watersheds from data rich to data poor environments is one of the most fundamental challenges in the field of hydrology. If a defensible watershed model can be developed for a site, the resulting model can be employed to solve an extremely wide class of hydrologic problems. Sivapalan (2003) argues that the new IAHS decadal initiative on "Predictions in Ungauged Basins' (PUB) (see Hubert et al., 2002) represents a grand challenge for the field of hydrology that forces us to deal with questions that are 'deep, grand and practical'. Sivapalan (2003) further argues that 'prediction in ungauged basins (PUB), sans calibration, remains a difficult, unsolved problem, demanding urgent resolution and requiring significant new breakthroughs in data collection, process knowledge and understanding.'

1.2 Assimilation of Hydrometerorological Data:

An important impetus for the recent interest in new approaches in the regionalization of hydrologic processes stems from the newly available sources of hydrologic data such as spatial digital geographic coverages and meteorological data including satellite and radar datasets. These new sources of hydrometeorological data combined with new developments in geographic information systems and database management systems have stimulated a significant research effort into the assimilation of these new sources of data into watershed model structures and land-surface schemes for regional climate models and general circulation models (GCM's). These developments have led to multi-institution partnerships such as the North American Land Data Assimilation System (NLDAS) which seeks to validate regional calibration schemes for a number of distributed hydrologic models (Mitchell et al., 2004).

1.3 The Land-Atmosphere Interface in Atmospheric Models:

Over the past few decades, there has been a tremendous amount of research relating to the improvement of numerical weather predictions based on regional climate models and GCM's. Since the land-atmosphere interface in these models has been shown to be very important to the accuracy of GCM model predictions, significant attention has been given to improving the performance of land surface schemes. As expected, investigators have found that land surface schemes in GCM models can perform well when data is available for model calibration and perform poorly when data is unavailable for model calibration (Gupta et al, 1999). Interestingly, Wood et al. (1998) conclude that the problem of how to transfer model parameters of land surface schemes from calibrated regions to uncalibrated regions is still unresolved. There are many new developments associated with regionalization approaches for land surface schemes which pertain to this chapter (Devonec and Barros, 2002; and Huang et al., 2003), however, a review of land surface schemes and GCM's is outside the scope of this chapter. Nevertheless, one can expect innovations from that literature to be quite useful for the regional watershed model calibration problem.

1.4 Advances in Regional Statistical Hydrology:

The problem of calibrating a watershed model to an ungauged watershed is analogous, and many ways identical, to the problem of estimating the probability distribution of flood flows at an ungaged site or to the problem of reconstructing a record of streamflow at an ungaged site using nearby gaged streamflow information. All such regional hydrologic problems require a hydrologic model combined with some form of regionalization method for transfer of the hydrologic model parameters from nearby hydrologically similar gaged watersheds to the ungaged watershed. Interestingly, nearly every regional hydrologic problem which has traditionally been addressed using regional statistical hydrologic methods can also be addressed using a watershed model. For example, one sees evidence of this in studies which employ watershed models for estimating design floods at ungaged sites (Calver et al., 1999; Blazkova and Beven, 2002; and Lamb and Kay, 2004).

Advances in the regionalization of watershed models should benefit from the relatively long and rich history associated with the development of regional statistical hydrologic methods. Most advances in regional statistical hydrology were introduced for the problem of estimating a flood frequency model at an ungaged site. Estimating a flood frequency distribution at an ungaged site is an obvious analog to the problem of estimating the parameters of a watershed model at an ungaged site. Most advances in regional statistical hydrology have now been applied to the regional watershed model calibration problem. Some examples of regional statistical hydrologic methods developed for the ungaged flood frequency problem include regional hydrologic regression methods (see Kroll and Stedinger, 1998, for review), index flood methods for estimating design floods at ungaged sites (Bocchiola, et. al., 2003), homogeneous regional pooling methods (Castellarin et al., 2001), Bayesian estimation of a joint flood frequency distribution (Campbell et al., 1999) and hydrologic record augmentation (Vogel and Stedinger, 1985), extension (Hirsch, 1982) and reconstruction (Hirsch 1979) methods for the transfer of hydrologic information from one site or region to another. Later sections of this chapter discuss how these and numerous other regional statistical methods can be employed to estimate regional models of watershed model parameters. The emphasis of this chapter is on regionalization methods for estimation of parameters of continuous rainfall-runoff watershed models. However, the reader is encouraged to explore the related literature dealing with the development of regional hydrologic relationships for estimating a wide range of other hydrologic statistics such as flood quantiles, low flow quantiles, constitutent loads, average streamflows, flow duration curves and unit hydrographs.

2. REVIEW OF METHODS FOR THE REGIONAL CALIBRATION OF WATERSHED MODELS

There are now numerous studies which provide brief reviews of the use of regional hydrologic methods for estimating watershed model parameters at ungauged sites including: Bloschl and Sivapalan (1995); Abdulla and Lettenmaier (1997a); Sefton and Howarth (1998); Xu and Singh (1998); Seibert (1999); Post and Jakeman (1999); Xu (1999); Fernandez et al. (2000) and Kokkonen et al. (2003). Previous regionalization studies have focused on a wide range of hydrologic models ranging from complex hourly and daily watershed models to the more parsimonous monthly water balance models.

Although each previous study attempted to regionalize a different watershed model, nearly all studies to date (with the exception of Fernandez et al., 2000) follow the same general approach. First a watershed model is calibrated to whatever climate and streamflow data is available for the region of interest. This step is followed by the application of a regional hydrologic method which attempts to relate the optimized watershed model parameters to watershed characteristics. Most studies apply a single regional hydrologic method which makes comparison among methods difficult. Some recent studies by Vandewiele and Elias (1995), Fernandez et al. (2000), Kokkonen et al (2003), and by Merz and Bloschl (2004) do enable comparisons among several methods of regionalization. The following sections describe each of the regional hydrologic methods which have been used to estimate watershed model parameters at ungauged sites. Following those sections, a summary is provided to ascertain which methods of regionalization hold the greatest promise for the future.

2.1 Regional Hydrologic Regression for Watershed Model Calibration

The most common regional hydrologic method employed to date is bivariate and multivariate regression. As discussed above, the application of regional regression methods are not limited to the problem of regional watershed model calibration. In fact, there is an even greater literature on the use of regional regression methods for estimation of flood flow statistics, hence the reader is encouraged to consult that literature as well as the literature discussed in this section relating to watershed model calibration.

The following studies have employed multivariate regression methods to relate watershed model parameters to watershed and climate characteristics: Jarboe and Haan, (1974); Heerdegen and Reich, (1974); Magette et al., (1976); Weeks and Ashkenasy, (1985); Weeks and Boughton, (1987); Institution of Engineers Australia, (1987); Karlinger et al., (1988); Servat and Dezetter (1993); Post and Jakeman, (1996); Tung et al. (1997); Abdulla and Lettenmaier (1997ab); Kull and Feldman, (1998); Post et al., (1998); Post and Jakeman, (1999); Fernandez et al., (2000); Mwakalila, (2003); Xu, (2003); and Merz and Bloschl (2004). Most of the above cited studies involve development of regional regression relationships for estimation of parameters of continuous rainfall-runoff watershed models, however, similar methods have been applied to estimation of event based regional unit hydrograph models (for example, see Heerdegen and Reich, (1974); Burn and Boorman, (1993); Kull and Feldman, (1998); and Tung et al. (1997))

Post et al. (1998) documents that incorporation of a regional relationship between annual runoff and forest density into model calibrations led to significant improvements in model application at ungauged locations. Servat and Dezetter (1993) found that it was easier to relate watershed model parameters to landscape attributes for parsimonious watershed models than for watershed models which are overparameterized. Merz and Bloschl (2004) found that the regression approach performed better than use of globally averaged parameter values, but not better than kriging and other methods described in the next section. Even when one attempts to regionalize a very reasonable and parsimonious watershed model, results are still mixed (Post and Jakeman, 1999) which led Fernandez et al. (2000) to introduce a new approach which involves estimating the watershed model parameters at all the sites in a region as well as the regional regression relationship all simultaneously.

Abudulla and Lettenmaier (1997a, 1997b) attempted to improve upon previous efforts by increasing the number of catchments in the region (34) and by using a more powerful calibration algorithm termed shuffled complex evolution developed by Duan et al. (1992). Schaake et al (1997) further demonstrated that a very large number of watersheds are necessary to obtain a meaningful relationships between watershed model parameters and watershed characteristics. To address this issue, Schaake et al (1997) compiled over 100 watersheds for the GEWEX Continental-Scale International Project (GCIP) which is now available for the scientific community and for the Model Parameter Estimation experiment (MOPEX) project study. Interestingly, Schaake et al. (1997) found that the watersheds in which regionalization methods performed best correspond to those watersheds in which the best calibrations were obtained.

2.2 Clustering, Kriging, Neural Networks and Hydrologically Homogeneous Regions

The simplest regionalization approach is to simply fix watershed model parameters to average values for a region. Merz and Bloschl (2004) found that using the same parameter set (either preset parameters or global average values of parameters) for all catchments in a hydrologically heterogeneous region, led to the poorest regionalization results for their analysis of 308 catchments in Austria. A more promising approach in data sparse environments is to assign apriori values to the watershed model parameters using some generalized homogeneity classification of watersheds based on land use, soil types, climate conditions, runoff ratios, etc. The idea is to cluster or group watersheds into 'hydrologically homogeneous' regions. A number of studies have shown that such an approach can lead to very poor watershed model performance (Gupta et al. 1999 and Nijssen et al., 2001) unless the watershed clustering approach is effective. Huang et al (2003) introduce the use of a self-organizing neural network map and a K-means clustering algorithm as a framework for transferring watershed model parameters to regions without data. Burn and Boorman (1993) showed that use of a watershed clustering algorithm to quantify watershed similarity led to improvements over the use of multivariate regression for estimation of two parameters of a unit hydrograph at ungaged sites in the United Kingdom. Vandewiele and Elias (1995) and Merz and Bloschl (2004) found that kriging led to an improvement over multivariate regression for estimation of parameters of monthly water balance models at ungaged sites. Merz and Bloschl (2004) found that use of average parameters of immediate upstream and downstream neighbors led to best performance among all regionalization methods tested.

2.3 Promising New Hybrid Approaches to Regional Calibration of Watershed Models

So far all previous watershed model regionalization studies have met with limited success. Kuczera and Mroczkowski (1998) suggested that attempts to regionalize watershed model parameters for the purpose of application to ungauged catchments will be *virtually impossible* due to the existence of multiple optimal model parameter sets and a high degree of correlation among model parameters. As a consequence, there exist many possible model parameter sets which produce virtually indistinguishable simulated streamflow sequences.

The above literature review reveals that methods for grouping catchments on the basis of their hydrologic homogeneity provide a promising approach to the regionalization of watershed models. There is a relatively rich literature on this subject relating to the regionalization of models of flood frequency (Tasker, 1982; Nathan and McMahon, 1990; and Burn and Boorman, 1993). For example, the 'region of influence' (ROI) approach introduced by Burn (1990) for regional flood frequency analysis allows each site to have a unique set of catchments belonging to its 'region'. This approach may have promise for regionalization of watershed models.

Another promising approach to hydrologic regionalization involves the use of hybrid methods such as in the study by Yu and Yang (2000) where first cluster analysis and principal component analyses were employed to break the region into three hydrologically homogeneous regions. Next, drainage area was used to develop a regional flow duration curve model which was in turn used to calibrate the watershed model at an ungaged site. Such a hybrid approach can benefit from advances relating to the definition of hydrologically homogeneous regions as well as from advances relating to the development of regional flow duration curve models for ungaged sites. Another hybrid approach is the regional calibration approach introduced by Fernandez et al. (2000) which is described in more detail below. Ideally, the regional calibration method described below would be combined with one of the methods for choosing a hydrologically homogeneous region described previously.

3. THE REGIONAL CALIBRATION APPROACH

All previous regionalization studies have taken the following approach. Initially a region is defined and a watershed model is calibrated to each catchment in that region. Next regional relationships between watershed model parameters and basin aand climatic characteristics are developed. The regional calibration approach involves fitting the watershed models and the regional regression models simultaneously. The idea is to choose among the virtually indistinguishable watershed model parameter sets so as to maximize the 'goodness-of-fit' of regional relationships between watershed model parameters and drainage basin characteristics. Instead of choosing parameters which minimize the model residuals alone, the goal is to both minimize model residuals ***and*** maximize the goodness-of-fit of relations between model parameters and basin characteristics, concurrently. Naturally this approach is computationally intensive, because all sites in the region must be calibrated concurrently, however, recent advances in computer technology and nonlinear optimization algorithms enable us to readily implement this approach. This methodology can be applied to any watershed model and could also be applied to the regionalization of other hydrologic models including flood frequency, low flow frequency, and stochastic streamflow models. Since Fernandez et al. (2000) found this approach to be so attractive, a case study is provided below to summarize the approach.

3.1 Case Study

This case study focuses on the regionalization of a four parameter monthly water balance model for a region made up of 33 sites in the southeastern U.S. shown in Figure 3.1. Further details can be found in the study by Fernandez et al. (2000).

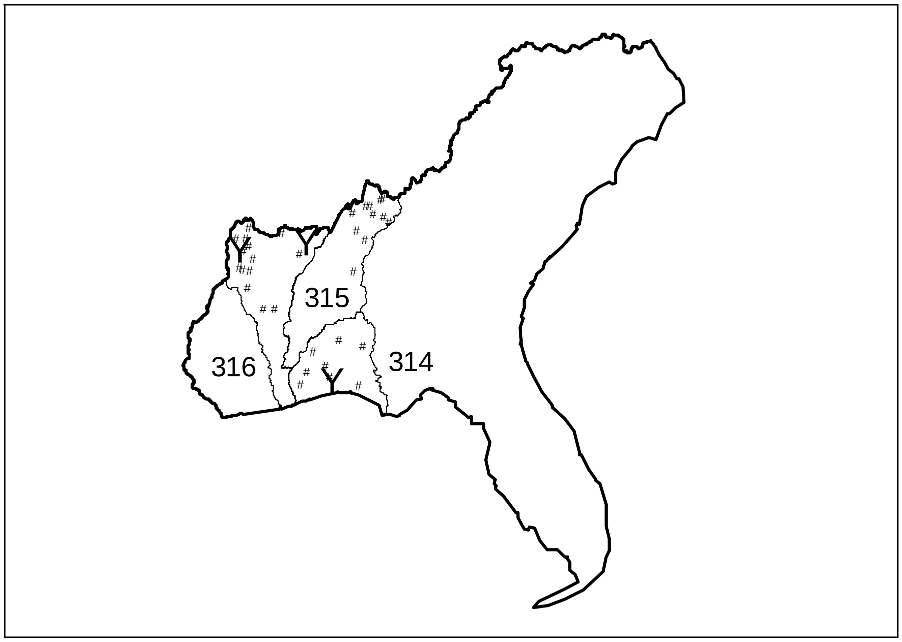


Figure 3.1 - Location of the 33 U.S. Geological Survey HCDN Streamgages located in Region 3 within Subregions 314, 315 and 316.

3.2 Description of Watershed Model

Alley (1984), Vandewiele et al. (1992), Vandewiele and Ni-Lar-Win (1998) and Xu and Singh (1998) compared the performance of numerous alternative monthly water balance models and concluded that a three to five parameter model is sufficient to reproduce most of the information in a hydrologic record on a monthly scale in humid regions. In those comparisons, all monthly models performed credibly and none stood out as clearly superior. This study employs the 'abcd' model introduced by Thomas (1981) and Thomas et al. (1983) because it is comparable with other water balance models and each of its parameters has a physical interpretation. Vandewiele et al. (1992) found that the 'abcd' model compares favorably with several other more recent monthly water balance models.

The 'abcd' model is a nonlinear watershed model which accepts precipitation and potential evapotranspiration as input, producing streamflow as output. Internally, the model also represents soil moisture storage, groundwater storage, direct runoff, groundwater outflow to the stream channel and actual evapotranspiration. Since the mathematical structure of the 'abcd' model is described by Thomas (1981), Thomas et al. (1983), Alley (1984, 1985), Fernandez et al. (2000), and Sankarasubramanian and Vogel (2002) complete details are not provided here.

3.3 Regional Physical Relationships for Model Parameters

The goal here is to present a new method for the calibration and regionalization of watershed models. An effort was made to use as much information as is available to relate watershed model parameters to basin characteristics. Normally, when one attempts to regionalize a watershed model for use at ungaged sites, one only includes landscape attributes which are easily measured from digital elevation maps, soil maps, climate atlases and other existing sources of information. This enables estimation of watershed model parameters at ungaged sites, where presumably no streamflow data is available. The main objective of this case study is to describe a methodology for the regionalization of a watershed model, hence the need to develop usable relationships at ungaged sites is not considered as a goal here. Instead, this study uses several basin descriptors which require an analysis of streamflow data.

The 'abcd' model has four parameters *a, b, c* and *d*, each having some physical interpretation. The parameter a $(0 \le a \le 1)$ reflects the "propensity of runoff to occur before the soil is fully saturated" (Thomas et al., 1983). Fernandez et al. (2000) found, as did Alley (1984), that the parameter *a* falls in the range [0.95,0.99] across broad regions of the U.S. One expects runoff to decrease as soil permeability increases, hence the parameter *a* is modeled using the regional regression model

$$a = \alpha_a - \beta_a \cdot P \tag{3.1}$$

where P is basin permeability and α_a and β_a are regional regression model parameters. Values of P are obtained from a digital grid of soil characteristics developed for the conterminous United States by Wolock (1997).

The parameter *b* is an upper limit on the sum of actual evapotranspiration and soil moisture storage in a given month. Presumably this parameter depends on the ability of the catchment to hold water within the upper soil horizon. In this case study the parameter *b* is modeled using the physical relation

$$b = \alpha_b + \beta_b \cdot P \tag{3.2}$$

where P is basin permeability and α_b and β_b are regional regression model parameters.

The parameter *c* is equal to the fraction of streamflow which arises from groundwater discharge in a given month. Over the long term c is then defined simply as the baseflow index (BFI) an index used commonly in studies which develop relationships between drainage basin characteristics and groundwater discharge to a stream channel (see for example Gustard et al., 1992). An algorithm developed by the Institute of Hydrology (1980) is employed to estimate the average annual BFI from the same records of daily streamflow used to calibrate the monthly water balance models. This algorithm is not based on the theory of groundwater outflow hence one would not expect c to exactly equal BFI. Instead *c* is modeled using

$$c = \alpha_c + \beta_c \cdot BFI \qquad (3.3)$$

where α_c and β_c are regional regression model parameters. Gustard et al., (1992) review numerous studies which document the value of the BFI in regional flood and low flow studies. Burn and Boorman (1993) also found the BFI useful for estimation of unit hydrograph parameters at partially gauged sites.

One can easily show that the reciprocal of the parameter *d* is equal to the average groundwater residence time. Vogel and Kroll (1992, 1996) and others have shown that during baseflow conditions when direct runoff is negligible and when groundwater outflow is linearly proportional to groundwater storage that the groundwater residence time is linearly related to the logarithm of the baseflow recession constant K_b. The regional regression for *d* is then

$$d = \alpha_d - \beta_d \cdot \ln(K_b) \qquad (3.4)$$

Estimates of the daily baseflow recession constant K_b are obtained for each of the rivers in this study using the estimator K_{b5} introduced by Vogel and Kroll (1996). This estimator assumes that the groundwater aquifer acts like a linear reservoir as does the 'abcd' model. This estimator of K_b was favored among several baseflow recession estimators compared by Vogel and Kroll (1996).

3.4 Data Sources

The 'abcd' model requires time-series of monthly precipitation, potential evapotranspiration and streamflow to enable calibration. The following sections describe these data sources.

3.4.1 Monthly Streamflow Data: The streamflow dataset consists of records of average monthly streamflow at 33 sites located in the southeastern region of the United States. Figure 3.1 uses the symbols # and Y to illustrate the location of the 30 calibration and 3 validation sites, respectively. Streamflow data were obtained from the hydroclimatologic data network (HCDN), developed by the U.S. Geological Survey (Slack et al., 1993). Streamflow gages included in the HCDN are intended for use in climate sensitive studies and represent only a small subset of all streamflow data available in electronic form from the U.S. Geological Survey.

The record lengths for the 33 stations ranged from 19 to 37 years with an average of 30.4 years. Drainage areas ranged from 155 to 39,847 km^2 with an average drainage area of 3031 km^2. The average watershed elevation ranged from 60 m to 584 m with an average value of 207 meters above mean sea level.

3.4.2 Monthly Climate Data: The average annual precipitation for the 33 watersheds ranges from 1,316 mm to 1,640 mm with an average value of 1,435 mm. Spatially weighted monthly time series of precipitation and potential evapotranspiration over the period 1951-1988 were developed using a geographic information system, a digital elevation map, and digital monthly time-series grids for precipitation, minimum and maximum monthly temperature. The monthly precipitation, minimum monthly temperature and maximum monthly temperature time series were obtained from 0.5 degree digital time series grids using the PRISM (Daly et al., 1994, 1997) climate analysis system. These grids were resampled to 0.1 degrees using bilinear interpolation. Spatially averaged values of each climate characteristic over each basin were obtained using the PRISM digital time-series grids and watershed boundaries derived from a 1-km digital elevation map of the U.S. The digital precipitation and temperature time-series grids were generated using the PRISM modeling system (Daly et al. 1994, 1997). PRISM (Parameter-elevation Regressions on Independent Slopes Model) is a climate analysis system that uses point data, a digital elevation model (DEM), and other spatial information to generate gridded estimates of annual, monthly, and event-based climatic parameters.

3.4.3 Monthly Potential Evapotranspiration: The spatially averaged time-series of monthly temperatures were combined with estimates of extraterrestrial solar radiation for each basin to obtain time-series of monthly potential evapotranspiration (PE) for each basin using the Hargreaves (Hargreaves and Samani, 1982) method. Extraterrestrial solar radiation was estimated for each basin by computing the solar radiation over 0.1 degree grids using a method introduced by Duffie and Beckman (1980), and then summing those estimates for each river basin. Even though it is only based on temperature and solar radiation measurements, numerous studies have shown that the Hargreaves method, performs well when compared with other more complex methods. For example, the Hargreaves method was the highest ranked temperature based method for computing PE reported in the ASCE Manual 70 analysis (Jensen et al., 1990). Allen (1993) showed that Hargreaves method performs well in a wide range of latitudes and climates for periods of 5 days or longer, without significant error. Among all temperature-based methods, the Hargreaves method is the only one recommended in the *Handbook of Hydrology* by Shuttleworth (1993).

3.5 Watershed Model Calibration Approaches

Traditional approaches to model calibration assume that the primary objective is to obtain a “best fit” to the streamflows at each site, thus the objective function tends to focus on the model residuals at each site. The traditional calibration objective function treats each site independently even if the goal is to obtain a regional hydrologic model. Our idea is to modify the objective function to reflect the fact that ones interest is in both a ‘best fit’ to the streamflows at each site **and** a ‘best fit’ to the regional relationships which relate model parameters to watershed characteristics.

Two approaches to model calibration are compared (1) traditional automatic calibration which estimates model parameters at each site which yield a "best fit" to streamflow observations and (2) a regional calibration methodology which estimates model parameters at all sites concurrently in an effort to obtain a good fit to streamflows at all sites while simultaneously obtaining a good fit to the relationship between model parameters and watershed characteristics.

3.5.1 At-Site Calibration Calibration algorithms have evolved considerably and it is now common practice to use a specially designed optimization algorithm, such as the shuffled complex evolution (SCE) algorithm developed at the University of Arizona for calibration of a watershed model (Duan et al., 1992). Unfortunately most algorithms such as the SCE algorithm are suited to calibration of a hydrologic model at a single site and are not suited to the computational burdens posed by the regional calibration methodology introduced later in this study. Instead a generalized reduced gradient nonlinear programming algorithm available as an extension to Excel (Premium Solver Plus Version 3.5, 1999) is employed. The Premium Solver Plus Version 3.5 is an extension to the standard Microsoft Excel Solver, with the capacity to solve much larger problems, up to 1,000 variables, at speeds anywhere from three to 100 times faster than the standard Solver. This algorithm is employed to calibrate the '*abcd*' model to the climate and streamflow traces at each of the 30 watersheds. This approach is termed the 'At-Site' calibration methodology. In this case the objective at each site is to

$$\textit{Minimize} \quad \sum_{t=1}^{n}\left(\ln(Q_t) - \ln(\hat{Q}_t)\right)^2 \tag{3.5}$$

where Q_t is observed monthly streamflow in month t and $\hat{Q}_t$ is modeled monthly streamflow in month t and n is the number of months of data available for calibration. The sum of the difference between logarithms of observed and modeled streamflow is minimized so as to give roughly equal weight to wet and dry months. Otherwise, without taking logarithms, reproduction of monthly mean flows during the dry summer months is poor.

At each site, the initial soil moisture storage S_o and the initial groundwater storage G_o are constrained to equal their average modeled values during the month of September, because model simulations always begin at the start of the water year on October 1. Therefore G_o and S_o represent the average ending groundwater and soil moisture storage, respectively, in September. This approach is physically plausible and avoids the need to optimize two extra model parameters, instead treating them as model constraints.

3.5.2 Regional Calibration: The traditional at-site approach described above, treats each site independently in an effort to obtain the best possible calibration at each site. The regional calibration approach attempts to get the best possible calibration at each site while simultaneously obtaining the best possible regional relationships between model parameters and basin characteristics. In this case the objective is to

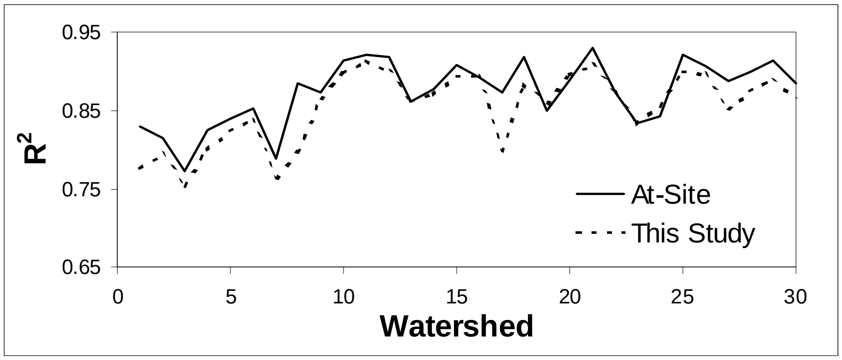
$$Maximize \quad \left[\frac{1}{m}\sum_{i=1}^{m} R_i^2\right] + \left[\frac{R_a^2 + R_b^2 + R_c^2 + R_d^2}{4}\right] \qquad (3.6)$$

where there are m=30 sites in the region and R_i^2 represents the coefficient of determination for site i which measures the goodness-of-fit of the logarithms of the modeled flows at site i and R_a^2, R_b^2, R_c^2, and R_d^2 represent the coefficient of determination associated with each of the regression models for the model parameters *a*, *b*, *c* and *d* given in equations (1), (2), (3) and (4), respectively. The idea of the objective function in (6) is to maximize the average goodness-of-fit of the 'abcd' model across all sites as well as to maximize the average goodness-of-fit of the four regional regression models. The coefficient of determination is used as a measure of the goodness-of-fit not because it is the best overall criterion, but because it provides a simple and equal weighting scheme for our two concurrent objectives.

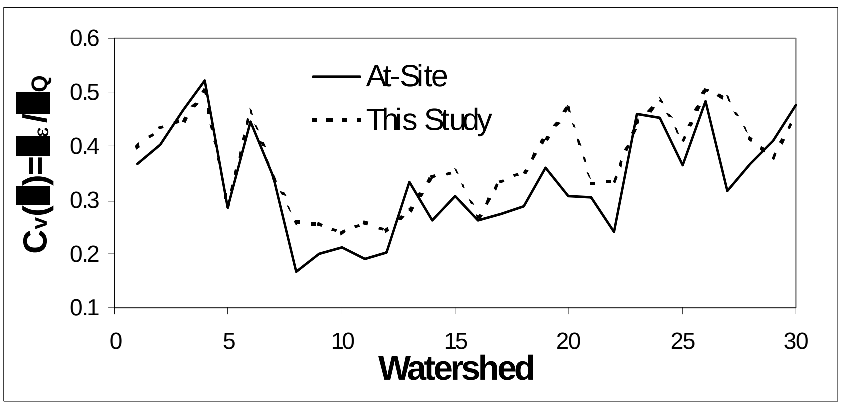
To implement the regional calibration approach one could use the SCE algorithm (Duan et al., 1992), however, since there are now 30(4)=120 model parameters to optimize, this approach is computationally infeasible. Instead a generalized reduced gradient nonlinear programming algorithm available as an extension to Excel (Premium Solver Plus Version 3.5, 1999) was employed.

3.6 Calibration Results

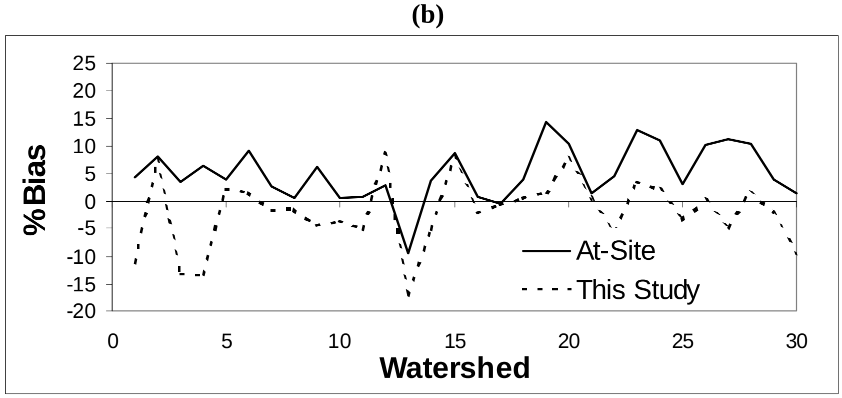
Figure 3.2 compares the "goodness-of-fit" of the monthly streamflows generated by the '*abcd*' model using the traditional at-site calibration approach and the regional calibration approach introduced in this study. Figure 2 uses three different statistics to represent the goodness-of-fit of the calibrated monthly flows to the observed flows (a) the coefficient of determination R^2 (b) the coefficient of variation of the model residuals computed using $C_v(\varepsilon)=\sigma_\varepsilon/\mu_Q$ where ε denotes model residuals and Q denotes streamflows and (c) the percentage bias. Since the model residuals ε should have mean zero, $\sigma_\varepsilon/\mu_\varepsilon$ is undefined. Instead, the $C_v(\varepsilon)=\sigma_\varepsilon/\mu_Q$ is computed by dividing by the mean of the monthly flows so that $C_v(\varepsilon)$ represents the standard deviation of the residuals as a fraction of the mean monthly streamflow. One observes from Figure 2, that in terms of both goodness-of-fit statistics R^2 and $C_v(\varepsilon)$, the at-site calibration approach is nearly always an improvement over the regional calibration approach. This is to be expected because the objective function in the at-site calibration algorithm seeks to obtain the 'best possible fit at each site. Nevertheless the goodness-of-fit corresponding to these two different calibration approaches are quite similar. Figure 2c documents the percent Bias computed using the formula $\%Bias = 100\left(\overline{\hat{Q}} - \overline{Q}\right)\big/\overline{Q}$ where $\overline{\hat{Q}}$ represents the mean of the model generated flows and $\overline{Q}$ represents the mean of the observed flows. Both calibration methods often result in bias because it is possible to obtain high values of R^2 even for a biased model. Overall, the regional calibration approach led, on average, to unbiased models for the entire region,



(a)



(b)



(c)

Figure 3.2 – Comparison of the Traditional At-Site Calibration and the Regional Calibration Approach Introduced Here Using the Goodness-of-Fit Statistics (a) Coefficient of Determination R^2, (b) Coefficient of Variation of Model Errors, $C_v(\varepsilon)=\sigma_\varepsilon/\mu_Q$, and (c) Percent Bias

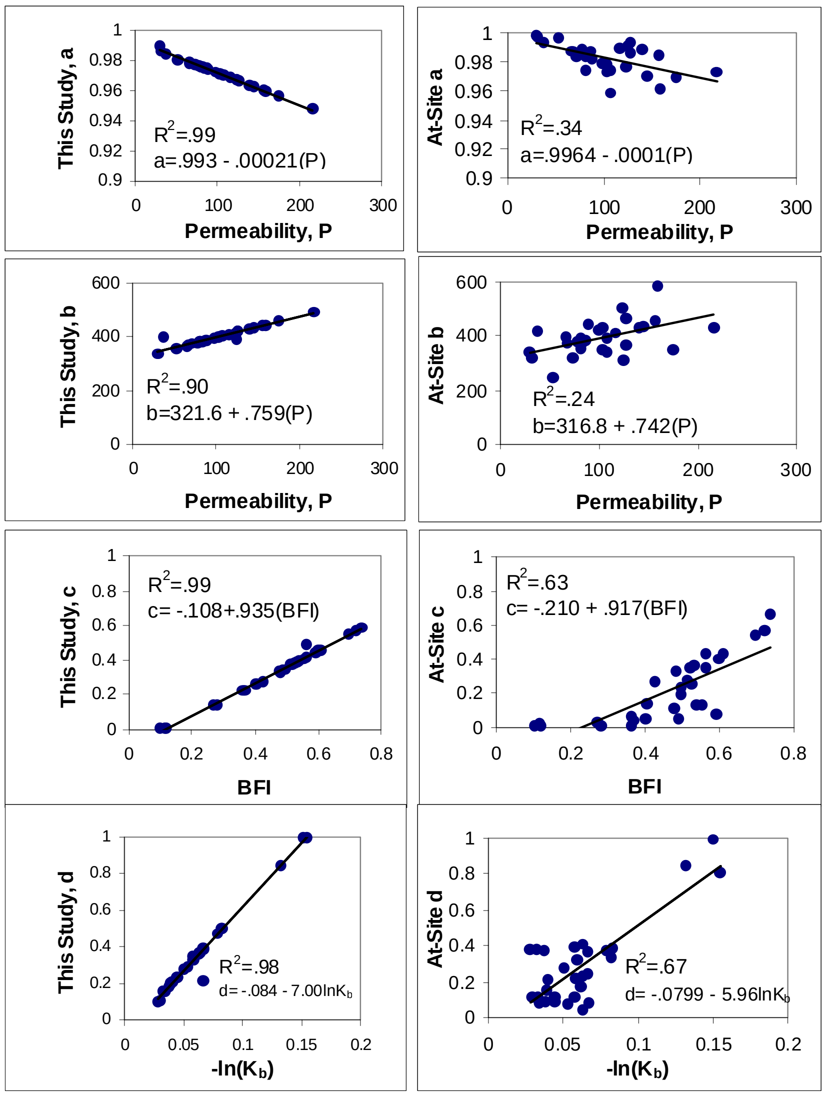


Figure 3.3– Relationships Between '*abcd*' Model Parameters and Watershed Characteristics Corresponding to At-Site (right-hand panels) and Regional Calibration (left-hand panels) Approaches

while the traditional at-site calibration approach resulted in upward bias. For individual sites, both approaches led to roughly the same variability in *%Bias*.
Figure 3.3 illustrates the remarkably precise relationships between calibrated model parameters and watershed characteristics which result from using a regional calibration strategy. When an at-site calibration strategy is applied, the right-hand panels of Figure 3.3 illustrate that the relationships between '*abcd*' model parameters and watershed characteristics are extremely weak. This result is consistent with the dozens of previous watershed model regionalization studies cited by Servat and Dezetter (1993), Abdulla and Lettenmaier (1997ab), Sefton and Howarth (1998), Xu and Singh (1998), Post et al. (1998), Xu (1999), Seibert (1999), Post and Jakeman (1999) Fernandez et al. (2000), Mwakalila (2003), Xu (2003), Merz and Bloschl (2004) and many others. In the left-hand panels of Figure 3.3 it is apparent that the regional calibration approach can produce extremely accurate regional regression relationships between watershed model parameters and watershed characteristics, while maintaining the goodness-of-fit between modeled and observed streamflows which is nearly as accurate as the best fit one can possibly achieve using an at-site algorithm. As is shown below, these nearly perfect regional regression relationships obtained using the regional calibration approach, are misleading, because they do not result in improvements in our ability to calibrate a watershed model at an ungaged site!

3.7 Model Validation

Research on hydrologic watershed models has evolved considerably, along with our awareness that model structures and their associated model parameter sets are not unique, infinite plausible mathematical representations exist. It is now generally understood that one can never validate a watershed model, rather, one can only invalidate it (see Kirchner et al., 1996; and Vogel and Sankarasubramanian 2003). In an effort to invalidate the watershed models estimated using the regional calibration approach described here, the methodology is evaluated using three basins which were not used to calibrate the model. The regional relationships between model parameters and watershed characteristics illustrated in Figure 3.3 were used to estimate watershed model parameters and to generate monthly streamflows at three validation sites and the results are illustrated in Figure 3.4. Here one observes that the traditional two-step regionalization approach produces nearly identical results to the regional calibration introduced in this study at all three validation sites. This result stems from the fact that the regional regression relationships between the model parameters and basin characteristics reported earlier in Figure 3.3 produce very similar regional relationships. So in spite of the fact that the traditional two-step regionalization approach leads to weak relationships between model parameters and basin characteristics, the relationships that do result are roughly equivalent to the tighter relations produced by the regional calibration method. Fernandez et al. (2000) show further that both the traditional two-step regionalization approach and the regional calibration approach introduced in this study reproduce the observed mean monthly streamflows with about the same accuracy at all three validation sites.

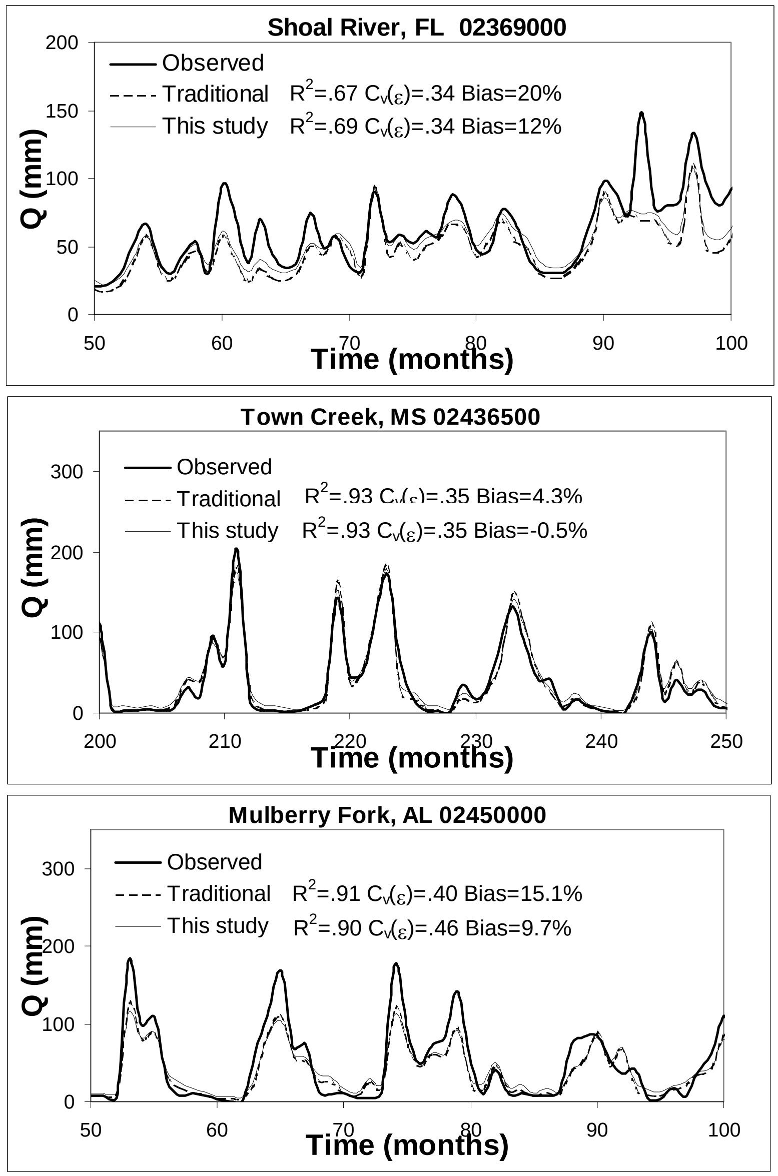


Figure 3.4 - Comparison of Simulated and Observed Monthly Streamflows Corresponding to the Traditional Regional Approach and the Regional Calibration Approach Introduced in this Study for Three Validation Sites.

Fernandez et al (2000) also document that both regionalization approaches tend to underestimate the standard deviation of the monthly streamflows. This is a general problem with **all** watershed models which can be proven as follows. Regardless of the model structure or temporal scale, streamflow can be expressed as

$$Q_t = f(P_t, PE_t \middle| \theta) + \varepsilon_t = \hat{Q}_t + \varepsilon_t \quad (3.7)$$

where $f(P, PE_t|\theta)$ denotes the deterministic watershed model with inputs P_t and PE_t, model parameter set θ and model error ε_t and $\hat{Q}_t$ denotes modeled streamflow. When model error is independent of the model as it should be

$$Var[\hat{Q}_t] = Var[Q_t] - Var[\varepsilon_t] \quad (3.8)$$

so that in general, $Var[\hat{Q}_t] < Var[Q_t]$ with the inequality becoming more important as model error increases. Therefore only a perfect watershed model without an error term ε_t will be able to reproduce the standard deviation of the observed streamflows.

4. CONCLUSIONS

Given the increasingly widespread usage of watershed models for solving environmental problems, the regionalization of watershed models may be one of the most challenging and fundamental problems within the entire field of hydrology. One important impetus for the recent interest in new approaches to the regionalization of watershed models stems from the newly available sources of hydrologic data such as spatial digital geographic coverages and meteorological data including satellite and radar datasets. Another impetus for the interest in watershed model regionalization results from recent advances relating to numerical weather predictions based on regional climate models, hydrologic land surface schemes and GCM's. As expected, investigators have found that hydrological land surface schemes in GCM models perform poorly when data is unavailable for model calibration (Gupta et al, 1999) and the problem of how to transfer model parameters of hydrologic land surface schemes from calibrated regions to uncalibrated regions is still unresolved (Wood et al., 1998).

Previous regionalization efforts have used a two-step approach where (1) the hydrologic model is fit to each site in a region and then (2) hydrologic model parameters are related to watershed characteristics. Dozens of such regionalization attempts have been made by previous investigators for hourly, daily, and monthly watershed models, all producing mixed results. Invariably the relationships between watershed model parameters and watershed characteristics are extremely weak as was illustrated again in this study in the right-hand panel of Figure 3. This chapter and Fernandez et al. (2000) introduced a new approach to the regionalization of a hydrologic model. The approach, termed regional calibration, attempts to calibrate the model at all sites in a region simultaneously, while concurrently attempting to achieve the best possible regional relationships among watershed model parameters and watershed characteristics. This approach led to remarkable improvements in the precision of the regional relationships between watershed model parameters and watershed characteristics when compared to the traditional two-step approach. However, the "remarkable" regional relationships corresponding to the regional calibration approach were later shown to be misleading, because validation experiments documented that both the traditional two-step approach and the regional calibration approach produce roughly equivalent streamflow simulations at three validation sites.

It is well known that there exist a very large number of watershed model parameter sets which can produce physically realistic simulations. The regional calibration approach provides an attractive approach for reducing the feasible subspace over which the watershed model calibration is performed. Kuczera (1997) documented that the addition of such constraints can lead to significant efficiencies in the overall watershed model parameter optimization problem. Even the regional calibration approach, with its inherent ability to reduce the feasible subspace of model parameters, results in a nonunique set of watershed model parameters. This apparent, yet ubiquitous, nonuniqueness of watershed model parameter sets will always confound our ability to estimate regional relationships between watershed model parameters and watershed characteristics.

It is unclear on the basis of this initial experiment, whether the regional calibration methodology introduced in here will ever lead to significant improvements in our ability to regionalize a watershed model over the traditional two-step approach. The regional calibration methodology introduced in this study could be extended to any problem involving the regionalization of a hydrologic model. The following recommendations should result in improvements in the regional calibration approach introduced here:

1. The regional calibration approach can lead to dramatic improvements in the goodness-of-fit of regional relationships between watershed model parameters and basin characteristics. However, such remarkably good regional relationships imply significant underestimation of the uncertainty associated with resulting watershed model parameter estimates at ungaged sites. Future attempts to implement the regional calibration strategy need to properly account for the statistical properties of the model error and the multicollinearity among the watershed model parameters and the multicollinearity among the basin descriptors to properly account for the uncertainty associated with the resulting regional relationships.
2. Previous regionalization studies have taken a different approach than this study. Most previous studies have considered as their primary goal, estimation of watershed model parameters at ungaged sites. The

results of such studies are rarely definitive because one never knows whether the goodness-of-fit of the regional relationships between watershed model parameters and basin characteristics could be improved by gathering better drainage basin information or by reformulating the structure of the regional relationships between watershed model parameters and basin characteristics. This study takes a different approach because it only sought to develop regional relationships between watershed model parameters and basin characteristics under idealized conditions when streamflow records are available for estimating some of the basin characteristics. If one cannot solve this 'data-rich' problem, one cannot hope to solve the 'data-poor' (ungaged site) problem. It was found that even though the regional calibration method introduced here appears to offer significant potential for improving relations between basin characteristics and watershed model parameters, it will not necessarily offer improvements in our ability to estimate model parameters at ungaged sites. If this experiment had been attempted for the 'data-poor' (ungaged site) problem, we could not have proven this point. Future researchers should consider solving the 'data-rich' problem described here, or a variant thereof, before attempting to solve the 'data-poor' problem which exists at a purely ungaged site.

3. Some of the most significant improvements in watershed modeling over the past few decades resulted from improvements in our ability to conceptualize and model hydrologic processes. Ultimately, improvements in our ability to regionalize watershed models will only come after hydrologists begin to conceptualize and model regional physical relationships between watershed model parameters and watershed characteristics. As was clearly demonstrated by Wallis (1965), multivariate regression methods are unable to uncover basic physical laws. In other words, until hydrologists formulate the basic theoretical (physical) relationships between watershed model parameters and watershed characteristics, regionalization studies will continue to produce mixed results. Vogel and Kroll (1996) demonstrated this concept to the analogous problem of estimating regional hydrologic models of low flow. They showed that improvements in regional models of low flow can be obtained by formulating spatial theoretical relationships among watershed model parameters and landscape attributes. One could provide citations to hundreds (possibly thousands) of different physically based watershed simulation models. Interestingly, we are unaware of any studies which formulate physically based regional hydrologic relationships between watershed simulation model parameters and their associated landscape attributes. Given this fact, it should come as no surprise that previous watershed model regionalization studies have met with limited success.
4. Of all the regional methods attempted to date, regression is the most widely used approach for relating watershed characteristics to

watershed model parameters. Regional regression models can be quite misleading because even when the regional relationships exhibit a high degree of fit those relations are not necessarily effective for generating calibrated watershed models at ungauged sites with good predictive capability (see Fernandez et al., 2000; and Kokkonen et al. 2003; for examples of this phenomenon). It is not enough to focus on goodness-of-fit associated with the regional regression models, one must also capture the covariance structure among watershed model parameters. Kokkonen et al. (2003) found that ignoring the covariance structure of the watershed model parameters in the development of regional regression relationships led to a significant decrease in the performance of the regionally "calibrated" watershed models.

5. A literature review reveals that methods for grouping catchments on the basis of their hydrologic homogeneity provide a promising approach to the regionalization of watershed models. Examples of this approach include use of kriging, neural networks, and the 'region of influence' (ROI) approach introduced by Burn (1990) for regional flood frequency analysis. The ROI approach allows each site to have a unique set of catchments belonging to its 'region'.
6. Improvements in regionalization methods for the calibration of watershed models are expected to result from the use of hybrid regionalization methods. Hybrid regioinalizatioon methods will combine recent advances in regional hydrologic statistics and the determination of hydrologically homogeneous regions with the regional calibration methodology introduced by Fernandez et al. (2000). To enable a proper accounting of the impact of both the serial and spatial covariance structure of watershed model residuals, future developments in the regionalization of watershed model parameters will need to draw upon analogous developments in regional hydrologic methods introduced by Kroll and Stedinger (1998) and others. Tung et al. (1997) document the importance of accounting for the covariance structure of the watershed model parameters when fitting regional regression models. The generalized least squares regression method (see Kroll and Stedinger, 1998) enables a proper accounting of both the spatial covariance among flow, climate and watershed characteristics as well as the temporal covariance associated with flow, climate and model residuals. Analogous developments are needed to enable improvements in the regionalization of watershed models. Future research will hopefully combine the regional calibration idea introduced here with methods such as seemingly unrelated regression (Tung et al., 1997) and generalized least squares regression (Kroll and Stedinger, 1998).

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