2-2018

Curve Number Approach to Estimate Monthly and Annual Direct Runoff

Andrew John Guswa
Smith College, aguswa@smith.edu

Perrine Hamel
Stanford University

Kate Meyer
University of Minnesota

Recommended Citation

Guswa, Andrew John; Hamel, Perrine; and Meyer, Kate, "Curve Number Approach to Estimate Monthly and Annual Direct Runoff" (2018). Engineering: Faculty Publications, Smith College, Northampton, MA.
https://scholarworks.smith.edu/egr_facpubs/15

Curve number approach to estimate monthly and annual direct runoff

Andrew J. Guswa[1], Perrine Hamel[2], Kate Meyer[3]

Abstract

This paper establishes a novel approach to estimate monthly and annual direct runoff by combining the curve number method of the Natural Resources Conservation Service with an exponential distribution of rainfall depths. The approach was tested against observed rainfall and runoff for 544 watersheds throughout the contiguous United States. For more than half of the watersheds, the performance of the new approach is indistinguishable from the application of the method to daily rainfall when curve numbers are determined via calibration. For all watersheds, the uncertainty introduced by the approximation of the distribution of rainfall depths is far less than the uncertainty associated with the use of tabulated curve numbers based on soil and land-cover characteristics. The new approach does not appreciably increase the overall uncertainty associated with the application of the curve number method in ungaged watersheds. The approach provides reasonable estimates of monthly and annual direct runoff that can inform land-management decisions when daily rainfall records are unavailable.

---

[1] Corresponding author, Picker Engineering Program, Smith College, Northampton, MA 01063, aguswa@smith.edu

[2] Natural Capital Project, Stanford University, Stanford, CA 94305

[3] Department of Mathematics, University of Minnesota, Minneapolis, MN 55455

Introduction

Changes to the landscape affect many hydrologic processes and ecosystem services (Daily 1997; National Research Council 2004; Martin-Ortega et al. 2015). Estimates of those effects, even when uncertain, benefit land-management decisions. With respect to water resources, effects of interest include changes to total streamflow, to flooding potential, and to the availability of baseflow at monthly to annual and multi-annual timescales (Brauman et al. 2007; Guswa et al. 2014; Bremer et al. 2016; Ouyang et al. 2016). Some decisions may require a precise and detailed analysis. Other contexts may tolerate greater uncertainty in order to reduce the time and resources required; these include land-management decisions in ungaged and data-poor locales, or rapid assessments across many ecologic and hydrologic processes that may be followed up by more detailed studies.

The Natural Resources Conservation Service (NRCS) curve number method estimates the direct runoff that results from an individual rainfall event as a function of land cover and soil characteristics (Natural Resources Conservation Service 2004a,b). The concepts have been incorporated into many popular hydrologic models, such as HEC-HMS (U.S. Army Corps of Engineers 2000), SWMM (Rossman 2007), HydroCAD (HydroCAD Software Solutions LLC 2011), SWAT (Neitsch et al. 2011), WinTR-20 (Natural Resources Conservation Service 2015), and the InVEST seasonal water yield model (Sharp et al. 2016). The method also has a number of known challenges (Ponce and Hawkins 1996; Hawkins et al. 2009). Specifically, not all watersheds exhibit the asymptotic approach to a constant curve number (Hawkins 1993), curve numbers determined from rainfall-runoff data show significant variability (Hjelmfelt 1991; Shaw and Walter 2009; Hawkins et al. 2009), use of tabulated curve numbers in ungaged watersheds is highly uncertain (Titmarsh et al. 1995; Hawkins et al. 2009; Tedela et al. 2012), and the method is misused and misapplied (Walter and Shaw 2005; Ogden and Stallard 2013). Despite these challenges, Hawkins et al. (2009) recognize the potential for the curve number method to inform land-management decisions.

This study extends the application of the curve number method for land-management decisions when the uncertainty of the event-based method is tolerable but rainfall event data are unavailable. This investigation tests whether direct runoff accumulated over a month or year can be estimated, without an appreciable increase in the uncertainty, by approximating the distribution of actual rainfall depths with an exponential distribution. Rather than requiring a full description of event-by-event precipitation, this new approach requires only total rainfall and an estimate of the number of events over the defined period of interest. The sections that follow explain this new approach and present results from tests on 544 U.S. watersheds.

Curve number method applied to event rainfall

The curve number method estimates the depth of direct runoff from a specified rainfall event (NRCS 2004b). Direct runoff refers to the water that reaches a stream quickly without specification of the pathway or origin of that water (Hawkins et al. 2009). For a given rainfall depth, P_i, the depth of direct runoff, Q_i, is calculated as

$$Q_i = g(P_i; CN) = \begin{cases} \dfrac{(P_i - \lambda S)^2}{(P_i + (1-\lambda)S)} & P_i > \lambda S \\ 0 & P_i \le \lambda S \end{cases} \tag{1}$$

where the subscript i refers to an individual event, S is maximum potential retention with dimensions of depth, and λS is the rainfall depth needed to initiate runoff, also called the initial abstraction. The maximum potential retention, S, is related to the curve number, CN, an empirical quantity that depends on land use and soil characteristics (NRCS 2004a,b):

$$S = \frac{1000}{CN} - 10 \qquad \text{(S in inches)} \qquad (2)$$

$$S = \frac{25\,400}{CN} - 254 \qquad \text{(S in millimeters)} \qquad (3)$$

In application, curve numbers are either calibrated to rainfall-runoff data or estimated from land-use and soil characteristics when streamflow data are unavailable (NRCS 2004a,b; Hawkins et al. 2009). Both cases require a choice for λ. The National Engineering Handbook indicates a value of 0.2 for λ, and tabulated values of curve numbers for different hydrologic soil groups and land covers are based on this value (NRCS 2004a,b). Recent results, however, indicate a smaller value of λ, closer to 0.05 (Jiang 2001; Hawkins et al. 2009; Shaw and Walter 2009; Dahlke et al. 2012). This study uses $\lambda = 0.05$. Using that value requires a modification of the curve numbers given in the handbook tables, and Jiang (2001) provides the following relationship:

$$CN_{0.05} = 0.0054 \cdot (CN_{0.2})^2 + 0.46 \cdot CN_{0.2} \qquad (4)$$

where $CN_{0.2}$ represents a tabulated curve number developed under the presumption that $\lambda = 0.2$ and $CN_{0.05}$ represents the curve number for use with $\lambda = 0.05$.

While the curve number method and tabulated values were developed to estimate runoff from large events, the method has been applied to a wide range of event magnitudes (Hawkins et al. 2009). Hawkins (1993), however, showed that estimates of curve numbers derived from rainfall and runoff data vary with event depth; curve numbers are typically larger for smaller events and approach constant values for larger events, though there are exceptions (e.g., Tedela et al. 2012). Thus, an estimate of runoff for a single, small event could have a large relative error. Runoff accumulations over multiple events, however, are dominated by large events, and the non-linearity of Eq. (1) represents this phenomenon. For example, the MacLeish Field

Station in West Whately, MA experienced seven rain events between 3 June and 27 June 2009 with magnitudes of 3.6, 4.0, 8.4, 11.2, 22.9, 38.6, and 58.7 mm (Guswa and Spence 2011). Applying Eq. (1) to each event, with a curve number appropriate for pasture ($CN_{0.05} = 59$), gives runoff estimates of 0.0, 0.0, 0.0, 0.0, 1.0, 4.3, and 11.0 mm, respectively. Over 93% of the total 16.4 mm of runoff is generated by the two largest events, and the contribution of the small events to the total error in accumulated runoff is small. Consequently, when event data are available, accumulated runoff over a longer time period (Q_N) can be estimated by direct application of the curve number method to n events over a period of N days,

$$Q_N = \sum_{i=1}^{n} Q_i \tag{5}$$

Curve number approach for monthly and annual runoff

This study presents an approach to estimate monthly and annual direct runoff when rainfall data are not available. This approach requires a tabulated curve number based on landscape characteristics (NRCS 2004a), total rainfall (P_N) over the period of interest (N days), and an estimate or measurement of either the mean event depth (α) or the frequency (η) of rainfall events (events per day). This new approach approximates the actual distribution of rainfall depths with an exponential distribution,

$$f(p) = \frac{1}{\alpha} exp\left(-\frac{p}{\alpha}\right) \tag{6}$$

where p is rainfall depth and α is the mean event depth, which can be estimated as

$$\alpha = \frac{P_N}{\eta N} \tag{7}$$

The exponential distribution is a recognized model of rainfall depths (e.g., Eagleson 1978; Richardson 1981; Rodriguez-Iturbe et al. 1999; Laio et al. 2001). Additionally, the exponential distribution is fully characterized by a single parameter, mean rain depth, making it useful in applications with limited data.

Combining event-based runoff (Eq. 1) with an exponential distribution of rainfall depths gives an expression for the mean runoff per event from the new approach,

$$\langle Q^{new}(\alpha; CN)\rangle = \int_{-\infty}^{\infty} g(p; CN) \cdot f(p; \alpha) dp \tag{8}$$

where angle brackets indicate expected value. Substituting Eqs. (1) and (6) into (8) gives

$$\langle Q^{new}\rangle = \int_{\lambda S}^{\infty} \frac{(p - \lambda S)^2}{(p + (1-\lambda)S)} \cdot \frac{1}{\alpha} exp\left(-\frac{p}{\alpha}\right) dp \tag{9}$$

Solving Eq. (9) results in the following expression for the mean runoff:

$$\langle Q^{new}\rangle = (\alpha - S) exp\left(-\frac{\lambda S}{\alpha}\right) + \frac{S^2}{\alpha} exp\left(\frac{(1-\lambda)S}{\alpha}\right) E_1\left(\frac{S}{\alpha}\right) \tag{10}$$

where $E_1(x)$ is the exponential integral (Abramowitz and Stegun 1972),

$$E_1(x) = \int_{x}^{\infty} \frac{exp(-u)}{u} du \tag{11}$$

Cumulative runoff over the period of interest is

$$Q_N^{new} = \langle Q^{new}\rangle \eta N \tag{12}$$

The strength of this new approach lies in its approximation of the distribution of large events. For the earlier example of seven rainfall events (3.6, 4.0, 8.4, 11.2, 22.9, 38.6, and 58.7 mm), event-by-event application of Eq. (1) results in an estimate of 16.4 mm of total runoff ($CN_{0.05}$ = 59). If Eq. (1) were applied directly to the mean rainfall depth of 21.1 mm, the estimate of cumulative runoff from seven such events would be just 5.6 mm; if Eq. (1) were applied directly to the total 147.4 mm of rainfall, estimated runoff would be 61.0 mm. Application of the new approach with an exponential distribution of depths results in an estimate of cumulative runoff of 17.4 mm, very close to the 16.4 mm estimated by application of the curve number method to each event individually.

Evaluation of new approach

Rainfall and runoff for U.S. watersheds

To test the new approach, this work used a dataset of daily meteorology and streamflow for 671 watersheds throughout the contiguous United States (Newman et al. 2014; Newman et al. 2015). Watersheds range in size from 1 to 25 000 km^2, with a median size of 335 km^2 and two-thirds of the watersheds between 100 and 1000 km^2 (Newman et al. 2015). Streamflow data are from the U.S. Geological Survey and the Daymet dataset is the source of meteorological data (Newman et al. 2015). The dataset includes precipitation and streamflow records from 1/1/1980 through 12/31/2010. Some of the records were eliminated or modified for this analysis after quality assurance checks; Appendix A includes details.

Runoff and baseflow were computed for two time scales of analysis: monthly and annual. Because the curve number method is not appropriate for snowmelt, analyses were limited to snow-free months and years. For the monthly analysis of each watershed, this study eliminated all months for which the snow-water equivalent was non-zero for some time during the month. Similarly, for the annual analysis, all years that were influenced by snow were removed. To ensure an adequate sample size of monthly runoff values for each watershed, monthly analyses were restricted to watersheds with more than ten months (total, not per year) of snow-free observations, and annual analyses were limited to watersheds with more than ten years of snow-free observations. Figure 1 presents a map of the watersheds used to test the approaches. Open circles represent watersheds included in the monthly analysis; filled circles represent watersheds included in both monthly and annual analyses.

Daily streamflow was separated into baseflow and direct runoff with a one-parameter recursive digital filter (Nathan and McMahon 1990) with a filter parameter of 0.925. This automated method of baseflow separation is objective, repeatable, and gives results similar to the smoothed minima method (Nathan and McMahon 1990). Summing direct runoff over each month and year produced records of observed monthly (Q_m^{obs}) and annual (Q_a^{obs}) direct runoff for each watershed.

Curve numbers determined from daily records

The objective of this investigation is to test whether the accumulated runoff estimated by using an exponential distribution of rainfall depths is equivalent to that determined by applying the curve number method directly to a record of daily rainfall depths. To separate the uncertainty introduced by the use of tabulated curve numbers from the uncertainty due to the approximation of the rainfall distribution, a curve number for each watershed was determined through calibration. Consistent with the intent of estimating accumulated runoff, the curve number for each watershed was determined by matching the cumulative direct runoff, estimated by applying the curve number to daily rainfall, to the cumulative observed runoff over the entire period of record. This calibration ensures that the average bias in the daily application of the curve number method is zero, i.e., the mean error between observed (monthly or annual) runoff and the runoff estimated by application of the curve number method to daily rainfall is zero.

Accumulated runoff is dominated by large events, and the largest events of the period of record strongly influence the calibration of the curve number.

With a calibrated curve number for each watershed, this study applied Eq. (1) to daily rainfall to compute daily runoff, which was then summed to create records of monthly and annual direct runoff. Monthly and annual errors were quantified by taking the difference between the monthly and annual estimates and observations:

$$\varepsilon_m^{daily} = \left(Q_m^{daily} - Q_m^{obs}\right) \tag{13}$$

$$\varepsilon_a^{daily} = \left(Q_a^{daily} - Q_a^{obs}\right) \tag{14}$$

where $Q_m{}^{daily}$ and $Q_a{}^{daily}$ represent the monthly and annual direct runoff, respectively, estimated by applying the curve number method to daily rainfall. By design, the mean values of $\varepsilon_m{}^{daily}$ and $\varepsilon_a{}^{daily}$ are zero for each watershed, as noted previously.

Application of the new approach

In the new approach, the actual, empirical distribution of daily rainfall depths is replaced with an exponential distribution, defined by a mean event depth, α, for each month or year. This average depth was calculated in two ways. One variation computed the mean rainfall depth by dividing the cumulative rainfall by the actual number of days with rain in each month or year. A second variation evaluated the utility of the new approach when information on number of events is approximate. In the monthly application, mean rainfall depth was computed with the average number of events for that month over all years in the dataset for that watershed (for example, the average number of events for all Septembers). Similarly, the average number of events per year was used in the annual application. The resulting two variations of the exponential distributions were used with calibrated curve numbers in Eqs. (10-12) to estimate monthly and annual runoff for each watershed. Thus, each watershed is associated with four records of monthly (and annual) runoff: observed runoff, runoff estimated by application of the curve number method to daily rainfall, runoff estimated from an exponential distribution of rain depths with mean rainfall depth determined by the actual number of events in each month (and year), runoff estimated from an exponential distribution of rain depths with mean rainfall depth determined by the average number of events.

Tests of the new approach

Both across watersheds and for each individual watershed, this study evaluated the performance of the new monthly and annual approaches by assessing 1) the mean error in monthly and annual runoff relative to observations, 2) the difference in squared errors of monthly and annual runoff between the new approach and the application of the curve number method to daily rainfall, and 3) the error in runoff relative to the uncertainty attributed to the use of tabulated curve numbers in ungaged watersheds. The descriptions that follow refer to monthly runoff, and the same tests apply to annual estimates as well. All tests were restricted to months (and years) with non-zero observed direct runoff.

The first tests assessed the mean error between observations and estimates from the new approach. A non-parametric bootstrap technique (Efron and Tibshirani 1993) was used to test the null hypothesis that the mean error in monthly runoff is indistinguishable from zero. Sampling (with replacement) the *m* monthly errors *m* times for all months and all watersheds generated a bootstrap estimate of the mean error. This process was repeated to generate 10 000 estimates of the mean error. A 95%-confidence interval for the mean error in monthly runoff was created from the 2.5% and 97.5% quantiles of the bootstrap estimates. The null hypothesis that the mean error is indistinguishable from zero was accepted if the confidence interval contained zero. Estimates of the mean monthly runoff were also regressed against the observed means for all watersheds. To assess the mean error for each individual watershed, 10 000 bootstrap estimates of the mean error were generated by sampling (with replacement) the *M* months of errors *M* times for each watershed. A 95%-confidence interval for the mean error was created from the 2.5% and 97.5% quantiles of the bootstrap estimates.

Even when Eq. (1) is applied to daily data and curve numbers are calibrated to ensure no bias in the mean monthly runoff, model structural error leads to uncertainty in estimated runoff for any given month. Approximating the rainfall depths with an exponential distribution further increases this uncertainty. While it is desirable for monthly errors in the new approach to be small, more important for this study is to test whether the errors from the new approach are comparable to those from the application of the curve number method to daily rainfall, i.e., to test whether the additional error due to the exponential approximation is small relative to the structural error of the curve number method. For each watershed, the square of the error between estimated and observed monthly runoff was determined, and the difference in squared-error between the daily method and the new approach computed:

$$\Delta_m^{se} = (Q_m^{new} - Q_m^{obs})^2 - \left(Q_m^{daily} - Q_m^{obs}\right)^2 \qquad (15)$$

This statistic is positive when the squared error in monthly runoff is larger for the new approach and negative when the error is larger for the daily application. To test whether the mean of squared errors from the new approach are significantly larger than those from the daily application of the curve number, 10 000 bootstrap samples of the mean difference in squared-error were generated. The null hypothesis that the error of the new approach is no larger than the error in the daily method (one-sided test) was rejected if the 5%-quantile of the mean difference in squared error was greater than zero. A linear regression of the square root of the mean-squared error (RMSE) from the new approach to the RMSE from the daily application of the method quantified the difference in uncertainty between the approaches.

A third test compared the mean error in runoff estimates with the uncertainty due to the use of tabulated curve numbers for ungaged basins. Tabulated curve numbers are a function of land-cover and soil characteristics and are reported for average antecedent runoff conditions, ARC II (NRCS 2004a). Titmarsh (1995) and Hawkins and Ward (1998, reproduced and cited in Hawkins et al. 2009) showed that the uncertainty in using tabulated curve numbers is large and comparable to the envelope of uncertainty created by using curve numbers that correspond to antecedent runoff conditions ARC I and ARC III (NRCS 2004b). Hjelmfelt (1991) showed that this envelope created by ARC I and ARC III represents the 10% and 90% exceedance probabilities for runoff. Runoff estimates from the new approach were tested against this envelope of uncertainty that resulted from the application of Eq. (1) to daily rainfall with curve numbers corresponding to ARC I and III for the calibrated curve numbers.

Results

Removing months and years with snow from the analyses left 544 watersheds with more than ten months of monthly runoff observations and 97 watersheds with more than ten years of annual data (Fig. 1). The total number of observations of monthly runoff across all watersheds and all months is 127 927; the number of total observations of annual runoff is 2270. Estimates of mean monthly runoff from the new approach show good agreement with the observed runoff (Fig. 2). Though the mean errors are statistically different from zero (95% confidence), they are small: 1.2 mm/month and 2.9 mm/month for use of the actual and average number of events, respectively (Table 1). The regression slopes of 1.11 to 1.20 indicate that the estimated mean monthly runoff is approximately 10-20% greater than observed (Table 1 and Fig. 2). Considering each watershed separately, the error in mean monthly runoff is indistinguishable from zero (95%-confidence interval) for 65% of the 544 watersheds when the actual number of rain events is used in the new approach (Table 2). When the average number of events per month is used, the error in mean monthly runoff is indistinguishable from zero (95%-confidence interval) for 26% of the 544 watersheds. For both monthly approaches, estimates of mean monthly runoff for all (100%) of the 544 watersheds fall within the envelope of uncertainty associated with using tabulated curve numbers (x's in Figure 2).

The RMSE of monthly runoff for the application of the calibrated curve number method to daily rainfall quantifies the structural error of the method. Fig. 3 indicates that this structural error is increased only slightly by the introduction of the exponential approximation. Regression slopes of 1.02-1.10 indicate that the RMSE of monthly runoff determined via the new approach is approximately 5-10% larger than the RMSE for monthly runoff determined via application of the curve number method to daily data (Table 1 and Figure 3). Mean monthly errors from the approach using the average number of events per month are larger than those from the approach that uses the actual number of events. The paired test of differences in monthly squared errors (Eq. 15) found that monthly squared errors from the new approach are not significantly larger than the errors from the daily application of the curve number method for 80% and 65% of the watersheds (actual and average number of events, respectively, 95%-confidence, 1-sided test, Table 2).

Tables 1 and 2 and Figs. 4 and 5 present results for the annual approaches. Fig. 4 indicates a good match in annual runoff between the new approach and observations. The mean errors in annual runoff are statistically different from zero (95% confidence, Table 1), and they are small: 10 mm/year and 8 mm/year for use of the actual and average number of events, respectively. Across the watersheds, mean annual runoff estimated via the new method is approximately 7% less than observed, as evidenced by a regression slope of 0.93 (Table 1). Mean error in annual runoff is indistinguishable from zero for 64% (actual number of events) and 65% (average number of events) of watersheds. Errors in annual estimates of direct runoff with the new approach are comparable to the errors associated with employing the curve number method to daily data (Fig. 5). The RMSE of annual runoff determined via the new approach is approximately 4 mm larger than the RMSE of annual runoff determined via application of the curve number method to daily data, indicated by regression slopes of 1.0 and intercepts of 4 mm (Table 1 and Fig. 5). The paired tests indicate that squared errors from the new approach are not significantly larger than the errors from the daily application of the curve number method for 74% and 88% of the watersheds (actual and average number of events, respectively, 95%-confidence, 1-sided test). Estimates of mean annual runoff for all (100%) of the 97 watersheds fall within the uncertainty envelope associated with use of tabulated curve numbers (x’s in Fig. 4).

Discussion

Figs. 2-5 indicate that the new approach presented in this work estimates monthly and annual direct runoff with a similar degree of certainty as the application of the curve number method to daily data for ungaged watersheds. The overestimation of runoff in the monthly results (Fig. 2 and Table 1) may indicate a deviation from the simplification of an exponential distribution of rainfall events. If actual rain events within a month are more similar to each other, i.e., if the empirical distribution has a smaller variance than the exponential, then the approach based on the exponential distribution would overestimate runoff, consistent with what is seen in Fig. 2.

Month-to-month and year-to-year errors in estimates from the new approach are similar to errors from the application of the curve-number method to daily rainfall (Tables 1 and 2 and Figs. 3 and 5). Most importantly, mean monthly and annual estimates of direct runoff lie well within the confidence interval attributed to uncertainty in the curve number (Figs. 2 and 4). This is consistent with earlier findings that estimated runoff is more sensitive to the selection of the curve number than to the precipitation depth (Hawkins 1975) and indicates that the approximation of an exponential distribution of rainfall depths does not appreciably increase the uncertainty associated with the application of the curve number method in ungaged watersheds. The large uncertainty in estimates of monthly and annual runoff for ungaged watersheds suggests that runoff estimates should be used with care.

While the new approach does not require daily rainfall data, it does require an estimate of the number of rain events within a given period of interest. Tables 1 and 2 and Figs. 2-5 indicate that estimates based on an average number of events are almost as good as those that use the actual number of events. Local estimates of the number of rain events could be obtained from traditional knowledge, global precipitation datasets (e.g., Gehne et al. 2016; The World Bank Group 2016), or historical records.

Many monthly (and annual) water-balance models have as a first step the partitioning of precipitation into direct runoff and retention (e.g., Ponce and Shetty 1995; Zhang et al. 2008; Sivapalan et al. 2011; Kirby et al. 2013; Chen and Wang 2015). These incorporate a relationship between monthly rainfall and direct runoff as a function of landscape characteristics (such as slope, soil type, land use) and state variables of the system (such as soil moisture and streamflow). The approach presented here provides a means for estimating or eliminating model parameters in these models. For example, the Dynamic Water Balance Model (DWBM; Zhang et al. 2008), relies on a parameter, α_1, to partition monthly precipitation into direct runoff and retention. This parameter must generally be determined via calibration, as attempts to relate the parameter to measurable watershed characteristics have proved challenging (Zhang et al. 2017). The approach presented here, with knowledge of the curve number and typical number of precipitation events, is another way to determine the amount of direct runoff from monthly precipitation.

Estimates of annual runoff from this new approach enable the partitioning of annual streamflow into direct runoff and baseflow. For example, a Budyko-type approach can estimate average annual streamflow based on average annual precipitation and potential evapotranspiration (e.g., Budyko 1974; Porporato et al. 2004; Szilagyi and Jozsa 2009; Hamel and Guswa 2015). Based on rainfall data from Monteverde, Costa Rica (Guswa et al. 2007), the Budyko curve predicts an increase in annual streamflow of 160 mm/yr following the conversion of forest to pasture (Table 3). The new approach presented in this study complements this result by estimating changes to direct runoff and, by subtraction, baseflow. For two soil groups (B and D), the new approach indicates a decrease in baseflow (40 mm/yr or 210 mm/yr for soil groups B and D, respectively), despite the increase in total streamflow. The large uncertainty associated with using a tabulated curve number (characterized by ARC I and III), however, prevents a definitive statement, as the confidence intervals for the change in baseflow include zero (Table 3). Nonetheless, the interpretation that baseflow is more likely than not to decrease when forest is converted to pasture may be sufficient to inform land-management decisions.

Conclusions

This study developed a new approach to estimate monthly and annual direct runoff by combining the NRCS curve number method with an exponential distribution of rainfall depths. Evaluation of the approach with daily rainfall and runoff data from 544 U.S. watersheds indicates that the error introduced by the exponential approximation is small and lies well within the uncertainty associated with application of the curve number method in ungaged watersheds. The simplicity and robust performance of the approach indicate that it can inform planning and land-management decisions in data-poor contexts.

Appendix A

Inspection of the dataset provided by Newman et al. (2014) revealed some questionable data. The authors either removed these basins from further analysis or modified the data as indicated in Tables A1-A2 below. In tables A1-A2, Q and P are the average daily streamflow and precipitation as reported in the file basin_annual_hydrometeorology_characteristics_daymet.txt (Newman et al. 2014). The variables, q and p, are the average daily streamflow and precipitation calculated from daily values of discharge (U.S. Geological Survey) and precipitation (Daymet), respectively, for each watershed over the entire period of record. For internal consistency, Q should be equal to q, and P should be equal to p; significant discrepancies were cause for removal of those watersheds from further analysis.”

References

Abramowitz, M. and Stegun, I. A. (1972). *Handbook of mathematical functions with formulas, graphs, and mathematical tables*. Dover Publications, New York, New York.

Brauman, K., Daily, G. C., Duarte, T. K., and Mooney, H. A. (2007). The nature and value of ecosystem services: An overview highlighting hydrologic services, *Annual Review of Environment and Resources*, 32, 67-98.

Bremer, L. L., Auerbach, D. A., Goldstein, J. H., Vogl, A. L., Shemie, D., Kroeger, T., Nelson, J. L., Benitez, S. P., Calvache, A., Guimarães, J., Herron, C., Higgins, J., Klemz, C., León, J., Lozano, J. S., Moreno, P. H., Nuñez, F., Veiga, F., and Tiepolo, G. (2016). One size does not fit all: Natural infrastructure investments within the Latin American Water Funds Partnership, *Ecosystem Services*, 17, 217-236.

Budyko, M. I. (1974). *Climate and life*, Academic Press, San Diego, California.

Chen, X., and Wang, D. (2015). Modeling seasonal surface runoff and base flow based on the generalized proportionality hypothesis, *Journal of Hydrology*, 527, 367-379, doi: 10.1016/j.jhydrol.2015.04.059.

Dahlke, H. E., Easton, Z. M., Walter, M. T., and Steenhius, T. S. (2012). Field test of the variable source area interpretation of the curve number rainfall-runoff equation, *Journal of Irrigation and Drainage Engineering*, 138(3), 235-244.

Daily, G. C., Ed. (1997). *Nature's services: societal dependence on natural ecosystems*, Island Press, Washington DC.

Eagleson, P. S. (1978). Climate, soil, and vegetation. 1. Introduction to water balance dynamics. *Water Resources Research*, 14(5), 705-12.

Efron, B., and Tibshirani, R. J. (1993). *An introduction to the bootstrap*, Monographs on statistics and applied probability 57, Chapman & Hall, New York, NY.

Gehne, M., Hamill, T. M., Kiladis, G. N., and Trenberth, K. E. (2016). Comparison of global precipitation estimates across a range of temporal and spatial scales, *Journal of Climate*, doi:10.1175/JCLI-D-15-0618.1.

Guswa, A. J., Rhodes, A. L., and Newell, S. (2007). Importance of orographic precipitation to the water resources of Monteverde, Costa Rica, *Advances in Water Resources*, 30, 2098-2112.

Guswa, A. J., and Spence, C. M. (2011). Effect of throughfall variability on recharge: application to hemlock and deciduous forests in western Massachusetts, *Ecohydrology*, 5(5), doi: 10.1002/eco.217.

Guswa, A. J., Brauman, K. A., Brown, C., Hamel, P., Keeler, B. L., and Sayre, S. S. (2014). Ecosystem services: Challenges and opportunities for hydrologic modeling to support decision making, *Water Resources Research*, 50, 4535-4544, doi:10.1002/2014WR015497.

Hamel, P., and Guswa, A. J. (2015). Uncertainty analysis of a spatially explicit annual water-balance model: case study of the Cape Fear basin, North Carolina, *Hydrology and Earth System Sciences*, 19, 839-853, doi: 10.5194/hess-19-839-2015.

Hawkins, R. H. (1975). The importance of accurate curve numbers in the estimation of storm runoff. *Water Resources Bulletin* 11(5), 887-891.

Hawkins, R. H. (1993). Asymptotic determination of curve numbers from data, *Journal of Irrigation and Drainage Engineering*, 119(2), 334-345.

Hawkins, R. H., Ward, T. J., Woodward, D. E., and Van Mullem, J. A. eds. (2009). *Curve number hydrology: State of the practice*, American Society of Civil Engineers, Reston, VA.

Hjelmfelt, A. (1991). Investigation of curve number procedure, *Journal of Hydraulic Engineering*, 117(6), 725-737.

HydroCAD Software Solutions LLC (2011). *HydroCAD Owner's Manual*, HydroCAD Software Solutions LLC, Chocorua, NH, 176 pages.

Jiang, R. (2001). *Investigation of runoff curve number initial abstraction ratio*, M.S. Thesis, School of Renewable Natural Resources, University of Arizona.

Kirby, J. M., Mainuddin, Md., Ahmad, M. D., and Gao, L. (2013). Simplified monthly hydrology and irrigation water use model to explore sustainable water management options in the Murray-Darling Basin, *Water Resources Management*, 27, 4083-3097, doi:10.1007/s11269-013-0397-x.

Laio, F., Porporato, A., Ridolfi, L., and Rodriguez-Iturbe, I. (2001). Plants in water-controlled ecosystems: Active role in hydrologic processes and response to water stress II. Probabilistic soil moisture dynamics, *Advances in Water Resources*, 24, 707-723.

Martin-Ortega, J., Ferrier, R. C., Gordon, I. J., and Khan, S. (2015). *Water ecosystem services: A global perspective*, Cambridge University Press, Cambridge, UK.

Nathan, R. J., and McMahon, T. A. (1990). Evaluation of automated techniques for base flow and recession analyses, *Water Resources Research*, 26(7), 1465-1473.

National Research Council (2004). *Valuing ecosystem services: Toward better environmental decision-making*. National Academies Press, Washington, DC.

Natural Resources Conservation Service (NRCS, 2004a). Chapter 9, Hydrologic soil-cover complexes, National Engineering Handbook, Part 630 Hydrology, , http://www.wcc.nrcs.usda.gov/ftpref/wntsc/H&H/NEHhydrology/ch9.pdf accessed on 27 August 2016.

Natural Resources Conservation Service (NRCS, 2004b). Chapter 10, Estimation of direct runoff from storm rainfall, National Engineering Handbook, Part 630 Hydrology, http://www.wcc.nrcs.usda.gov/ftpref/wntsc/H&H/NEHhydrology/ch10.pdf accessed on 14 March 2016.

Natural Resources Conservation Service (2015). WinTR-20 User Guide, ver 3.10, http://www.wcc.nrcs.usda.gov/ftpref/wntsc/H&H/WinTR20/WinTR20UserGuideVer310Mar2015.pdf, accessed on 14 March 2016.

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., and Williams, J. R. (2011). Soil and Water Assessment Tool theoretical documentation ver 2009. Texas Water Resources Institute Technical Report No. 406, http://swat.tamu.edu/media/99192/swat2009-theory.pdf accessed on 14 March 2016.

Newman, A. J., Sampson, K., Clark, M. P., Bock, A, Viger, R. J., and Blodgett, D. (2014). A large-sample watershed-scale hydrometeorological dataset for the contiguous USA. Boulder, CO: UCAR/NCAR. http://dx.doi.org/10.5065/D6MW2F4D.

Newman, A. J., Clark, M. P., Sampson, K., Wood, A., Hay, L. E., Bock, A., Viger, R. J., Blodgett, D., Brekke, L., Arnold, J. R., Hopson, T., and Duan, Q. (2015). Development of a large-sample watershed-scale hydrometeorological dataset for the contiguous USA: dataset characteristics and assessment of regional variability in hydrologic model performance. *Hydrology and Earth System Sciences*, 19, 209-223, doi: 10.5194/hess-19-209-2015.

Ogden, F., and Stallard, R. F. (2013). Land use effects on ecosystem service provisioning in tropical watersheds, still an important unsolved problem, *Proceedings of the National Academy of Sciences*, 110(52), E5037.

Ogden, F. L., Crouch, T. D., Stallard, R. F., and Hall, J. S. (2013). Effect of land cover and use on dry season river runoff, runoff efficiency, and peak storm runoff in the seasonal tropics of Central Panama, *Water Resources Research*, 49, 8443-8462, doi:10.1002/2013WR013956.

Ouyang, Z., Zheng, H., Xiao, Y., Polasky, S., Liu, J., Xu, W., Wang, Q., Zhang, L., Xiao, Y., Rao, E., Jiang, L., Lu, F., Wang, X., Yang, G., Gong, S., Wu, B., Zeng, Y., Yang, W., and Daily, G. C. (2016). Improvements in ecosystem services from investments in natural capital. *Science*, 352, 6292, 1455-1459.

Ponce, V. M., and Hawkins, R. H. (1996). Runoff curve number: Has it reached maturity?, *Journal of Hydrologic Engineering*, 1(1), 11-19.

Ponce, V. M., and Shetty, A. V. (1995). A conceptual model of catchment water balance: 1. Formulation and calibration, *Journal of Hydrology*, 173, 27-40.

Porporato, A., Daly, E., and Rodriguez-Iturbe, I. (2004). Soil water balance and ecosystem response to climate change, *American Naturalist*, 164, 625-632.

Richardson, C. W. (1981). Stochastic simulation of daily precipitation, temperature, and solar radiation, *Water Resources Research*, 17(1), 182-190.

Rodriguez-Iturbe, I., Porporato, A., Ridolfi, L., Isham, V., and Cox, D. (1999). Probabilistic modeling of water balance at a point: The role of climate, soil and vegetation. *Proceedings of the Royal Society of London A*, 455, 3789-3805.

Rossman, L. A. (2007). Storm water management model user's manual, EPA/600/R-05/040, U.S. Environmental Protection Agency, Cincinnati, OH.

Sharp, R., Tallis, H. T., Ricketts, T., Guerry, A. D., Wood, S. A., Chaplin-Kramer, R., Nelson, E., Ennaanay, D., Wolny, S., Olwero, N., Vigerstol, K., Pennington, D., Mendoza, G., Aukema, J., Foster, J., Forrest, J., Cameron, D., Arkema, K., Lonsdorf, E., Kennedy, C., Verutes, G., Kim, C. K., Guannel, G., Papenfus, M., Toft, J., Marsik, M., Bernhardt, J., Griffin, R., Glowinski, K., Chaumont, N., Perelman, A., Lacayo, M., Mandle, L., Hamel, P., Vogl, A. L., Rogers, L., and Bierbower, W. (2016). InVEST 3.3.0 User's Guide. The Natural Capital Project, Stanford University, University of Minnesota, The Nature Conservancy, and

World Wildlife Fund. http://www.naturalcapitalproject.org/invest/ accessed on 14 March 2016.

Shaw, S. B., and Walter, M. T. (2009). Improving runoff risk estimates: Formulating runoff as a bivariate process using the SCS curve number method, *Water Resources Research*, 45, W03404, doi:10.1029/2008WR006900.

Sivapalan, M., Yaeger, M. A., Harman, C. J., Xu, X., and Troch, P. A. (2011). Functional model of water balance variability at the catchment scale: 1. Evidence of hydrologic similarity and space-time symmetry, *Water Resources Research*, 47, W02522, doi:10.1029/2010WR009568.

Szilagyi, J. and Jozsa, J. (2009). Complementary relationship of evaporation and the mean annual water-energy balance, *Water Resources Research*, 45, W09201, doi: 10.1029/2009WR008129.

Tedela, N. H., McCutcheon, S. C., Rasmussen, T. C., Hawkins, R. H., Swank, W. T., Campbell, J. L., Adams, M. B., Jackson, C. R., and Tollner, E. W. (2012). Runoff curve numbers for 10 small forested watersheds in the mountains of the eastern United States, *Journal of Hydrologic Engineering*, 17(11), 1188-1198.

Titmarsh, G. W., Cordery, I., and Pilgrim, D. H. (1995). Calibration procedures for rational and USSCS design flood methods, *Journal of Hydraulic Engineering*, 121(1), 61-70.

U.S. Army Corps of Engineers (2000). Hydrologic modeling system HEC-HMS, Technical reference manual, US Army Corps of Engineers, Hydrologic Engineering Center, Davis, CA, 155 pages.

Walter, M. T., and Shaw, S. B. (2005). Discussion: “Curve number hydrology in water quality modeling: Uses, abuses, and future directions” by David C. Garen and Daniel S. Moore, *Journal of the American Water Resources Association (JAWRA)*, 41(6), 1491-1492.

Wang, J., and Georgakakos, K. P. (2007). Estimation of potential evapotranspiration in the mountainous Panama Canal watershed, *Hydrological Processes*, 21, 1901-1917, doi:10.1002/hyp.6394.

World Bank Group (2016). Climate Change Knowledge Portal. Available at: http://sdwebx.worldbank.org/climateportal/

Zhang, L., Potter, N., Hickel, K., Zhang, Y., and Shao, Q. (2008). Water balance modeling over variable time scales based on the Budyko framework – Model development and testing, *Journal of Hydrology*, 360, 117-131.

Zhang, L., Hickel, K., and Shao, Q. (2017). Predicting afforestation impacts on monthly streamflow using the DWBM model, *Ecohydrology*, 10(2), doi:10.1002/eco.1821.

Tables

Table 1: Assessment of mean error and root-mean-squared error of monthly and annual runoff across watersheds.

			Regression of estimated mean runoff from new approach against observed (Figs. 2 and 4)		Regression of RMSE from new approach against RMSE from daily method (Figs. 3 and 5)	
Temporal Resolution	Number of events	Mean error (observed-estimated) and [95%-confidence interval]	Slope [95% confidence interval]	Intercept [95% confidence interval]	Slope [95% confidence interval]	Intercept [95% confidence interval]
Monthly	Actual	-1.24 mm [-1.32, -1.16]	1.13 [1.11, 1.14]	-0.3 mm [-0.5, -0.2]	1.03 [1.02, 1.04]	0.04 mm [-0.08, 0.16]
Monthly	Average	-2.87 mm [-2.95, -2.78]	1.19 [1.17, 1.20]	0.4 mm [0.2, 0.6]	1.07 [1.05, 1.10]	0.5 mm [0.13, 0.78]
Annual	Actual	10 mm [8, 13]	0.93 [0.89, 0.97]	-1 mm [-8, 6]	1.06 [0.98, 1.13]	4 mm [0, 8]
Annual	Average	8 mm [6, 11]	0.93 [0.89, 0.97]	1 mm [-5, 8]	1.00 [0.92, 1.08]	4 mm [-1, 8]

Table 2: Mean error, magnitude of squared error, and mean error versus the uncertainty in curve number for each watershed.

		Percent of watersheds for which		
Temporal Resolution	Number of events	Mean error in runoff is indistinguishable from zero (95%-confidence interval)	Squared error from new method is less than or equal to squared error from daily method (95%-confidence interval, 1-sided)	Mean runoff is within confidence interval defined by uncertainty in CN (ARC I and III)
Monthly	Actual	65%	80%	100%
Monthly	Average	26%	65%	100%
Annual	Actual	64%	74%	100%
Annual	Average	65%	88%	100%

Table 3: Example of conversion of forest to degraded pasture. Rainfall data are representative of Monteverde, Costa Rica: 2700 mm/yr and 280 events/year (Guswa et al. 2007); potential evapotranspiration is representative of tropical forest and pasture (Wang and Georgakakos 2007; Ogden et al. 2013). Streamflow is estimated from the Budyko curve (Budyko 1974). Values of $CN_{0.2}$ are taken from Table 9-1 in NRCS (2004a); values of $CN_{0.05}$ are computed via Equation (4).

Land Cover	Hydrol. Soil Group	$CN_{0.2}$ [ARC I, ARC III]	$CN_{0.05}$ [ARC I, ARC III]	Potential evapo-transpiration (mm/yr)	Streamflow (mm/yr)	Direct runoff (mm/yr) [confidence interval from ARC I, III]	Change in baseflow, woods to pasture (mm/year) [confidence interval from ARC I, III]
Woods, good quality	B	55 [35,74]	42 [23,64]	1100	1710	20 [0,150]	-40 [-360,120]
Pasture, poor quality	B	79 [62,91]	70 [49,87]	900	1870	220 [40,670]	
Woods, good quality	D	77 [59,89]	67 [46,84]	1100	1710	180 [30, 550]	-210 [-490,20]
Pasture, poor quality	D	89 [76,96]	84 [66,94]	900	1870	550 [170, 1200]	

Guswa, Hamel, and Meyer
Curve number approach to estimate monthly and annual direct runoff

Figure captions

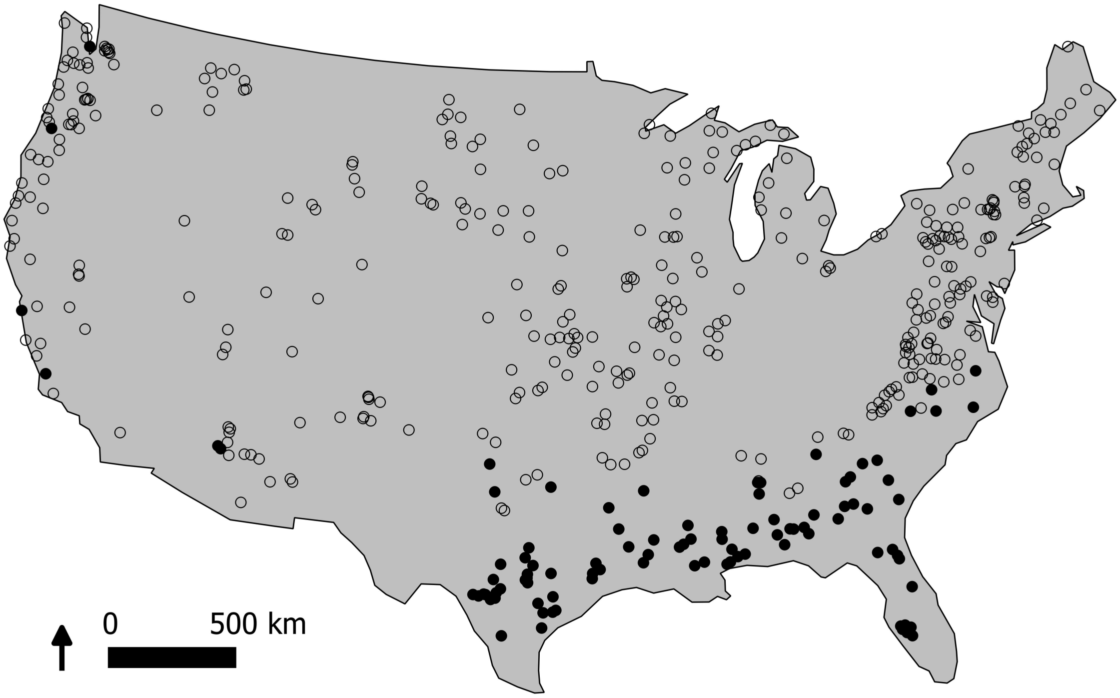
Figure 1
U.S. watersheds used in testing of the curve number approach. Gages indicated by an open circle represent the 544 watersheds used in the monthly analysis. Gages indicated by a closed circle represent the 97 watersheds used in both monthly and annual analyses.

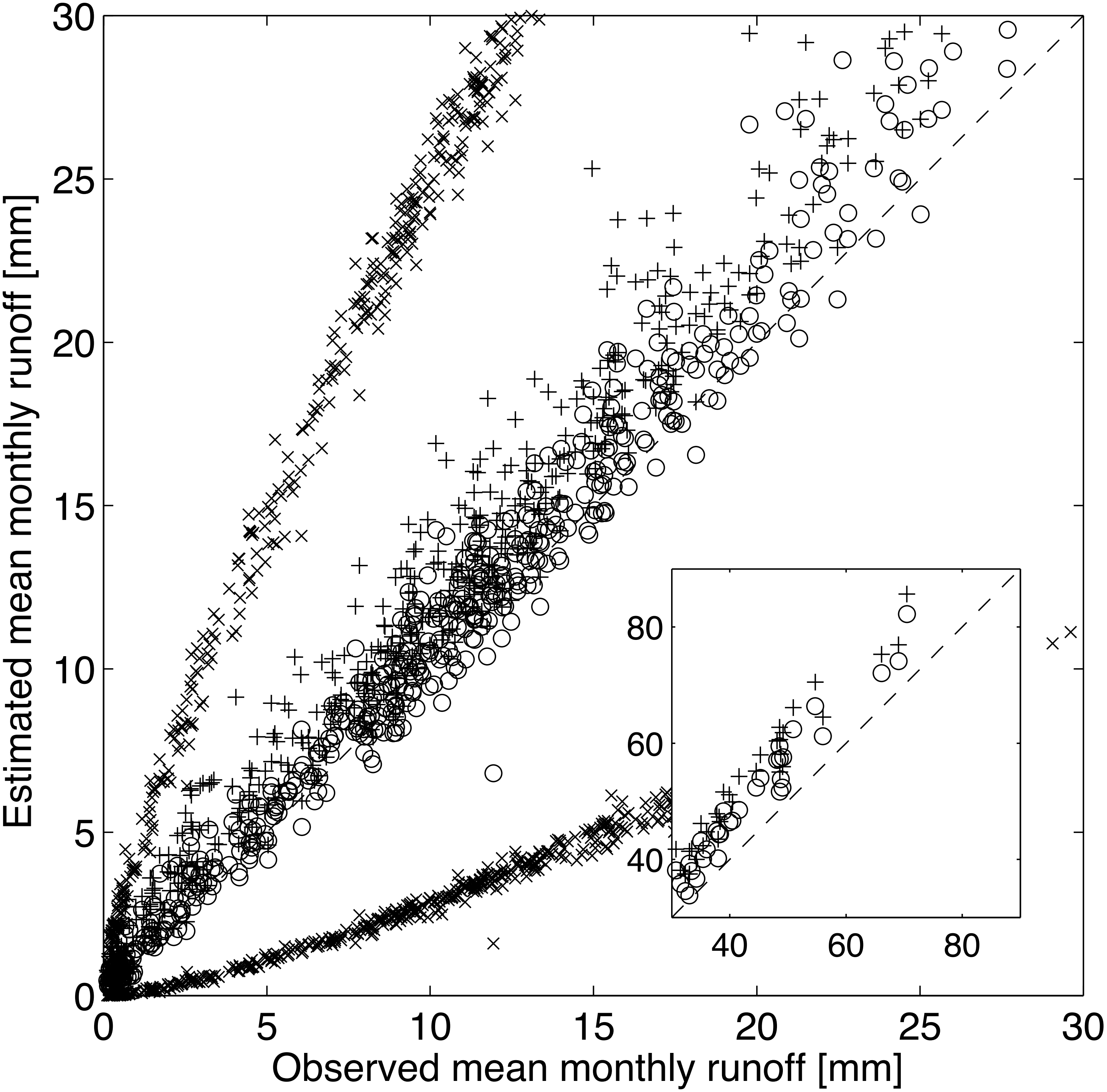
Figure 2
Mean monthly direct runoff estimated by new approach versus observed mean monthly direct runoff for 544 U.S. watersheds. Circles represent estimates for which the actual number of rain events per month were used; pluses represent estimates that use the average number of events per month. The uncertainty envelope associated with tabulated curve numbers is given by the x's.

Figure 3
Comparison of root-mean-squared error (RMSE) for estimates of monthly direct runoff from the application of the curve number method to daily rainfall data to RMSE from the new approach for 544 U.S. watersheds. Circles represent estimates using the actual number of rain events per month; pluses represent estimates that use the average number of events per month.

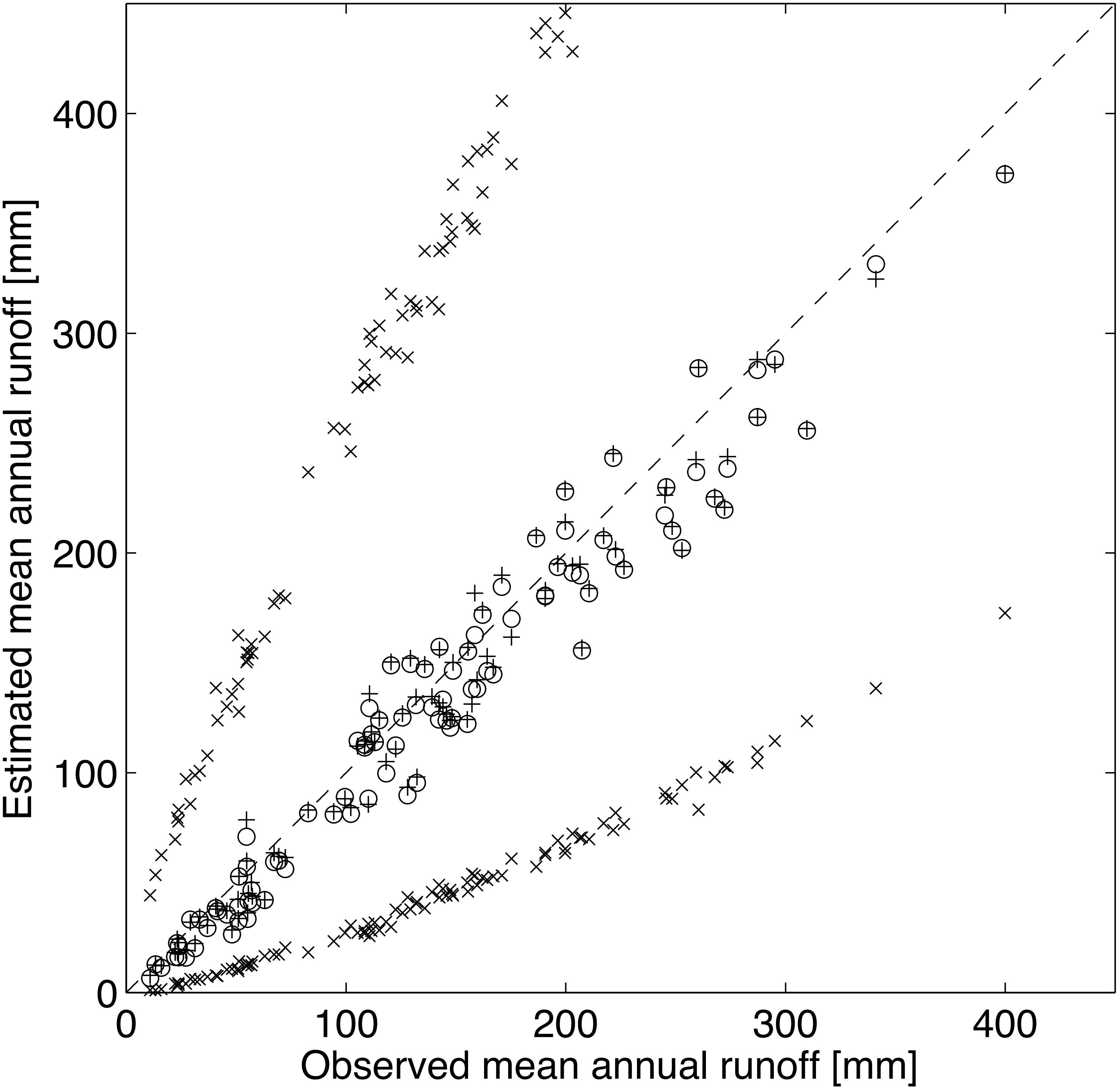
Figure 4
Mean annual direct runoff estimated by new approach versus observed mean annual direct runoff for 97 U.S. watersheds. Circles represent estimates using the actual number of rain events per year; pluses represent estimates that use the average number of events per year. The uncertainty envelope associated with tabulated curve numbers is given by the x's.

Figure 5
Comparison of root-mean-squared error (RMSE) in estimates of annual direct runoff from the application of the curve number method to daily rainfall data to RMSE from the new approach for 97 U.S. watersheds. Circles represent estimates using the actual number of rain events per year; pluses represent estimates that use the average number of events per year.

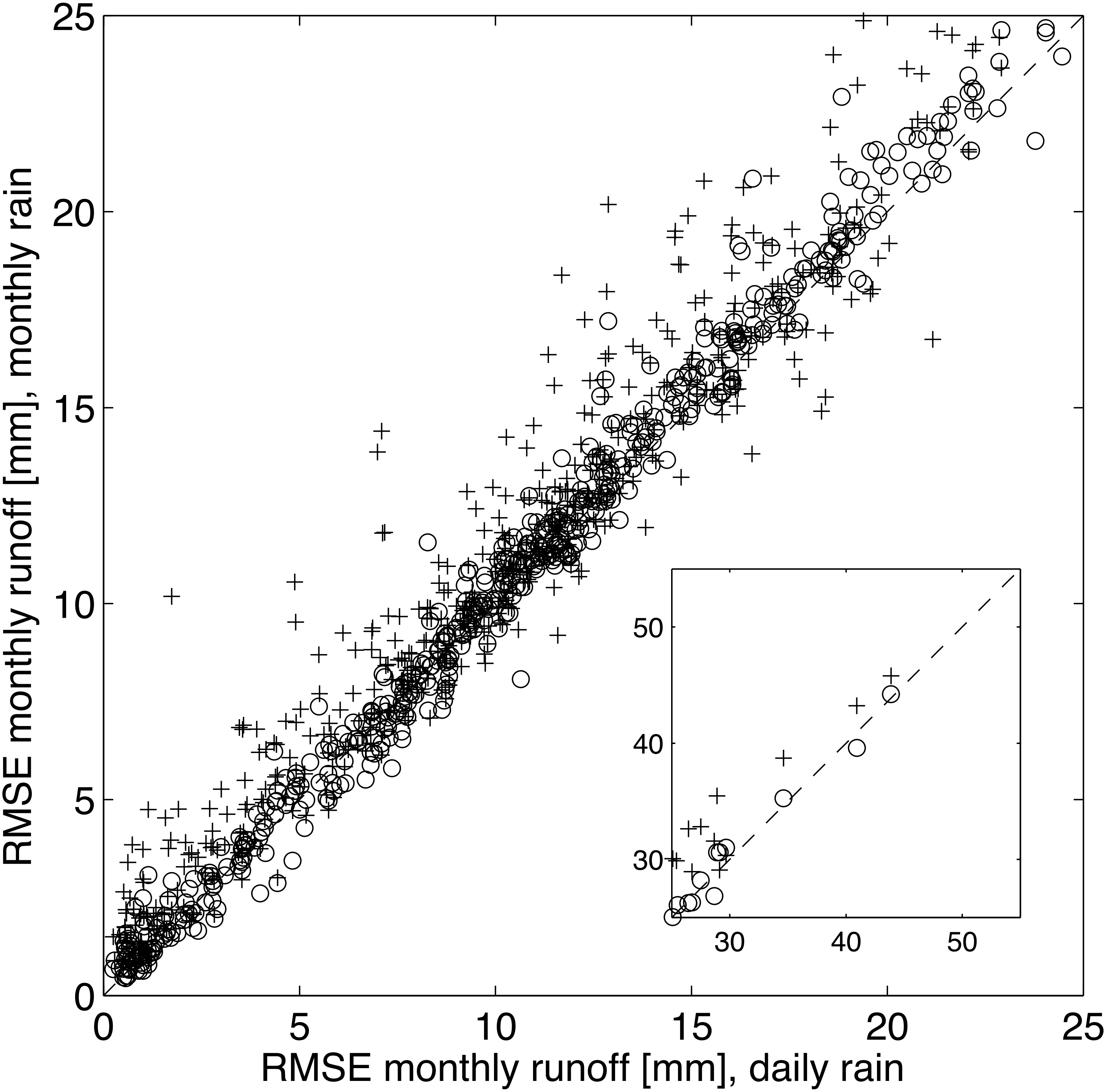

0
500 km



Estimated mean monthly runoff [mm]
Observed mean monthly runoff [mm]
0
5
10
15
20
25
30
0
5
10
15
20
25
30
40
60
80
40
60
80



Estimated mean annual runoff [mm]
0
100
200
300
400
0
100
200
300
400
Observed mean annual runoff [mm]


RMSE monthly runoff [mm], monthly rain
RMSE monthly runoff [mm], daily rain
0
5
10
15
20
25
0
5
10
15
20
25
30
40
50
30
40
50

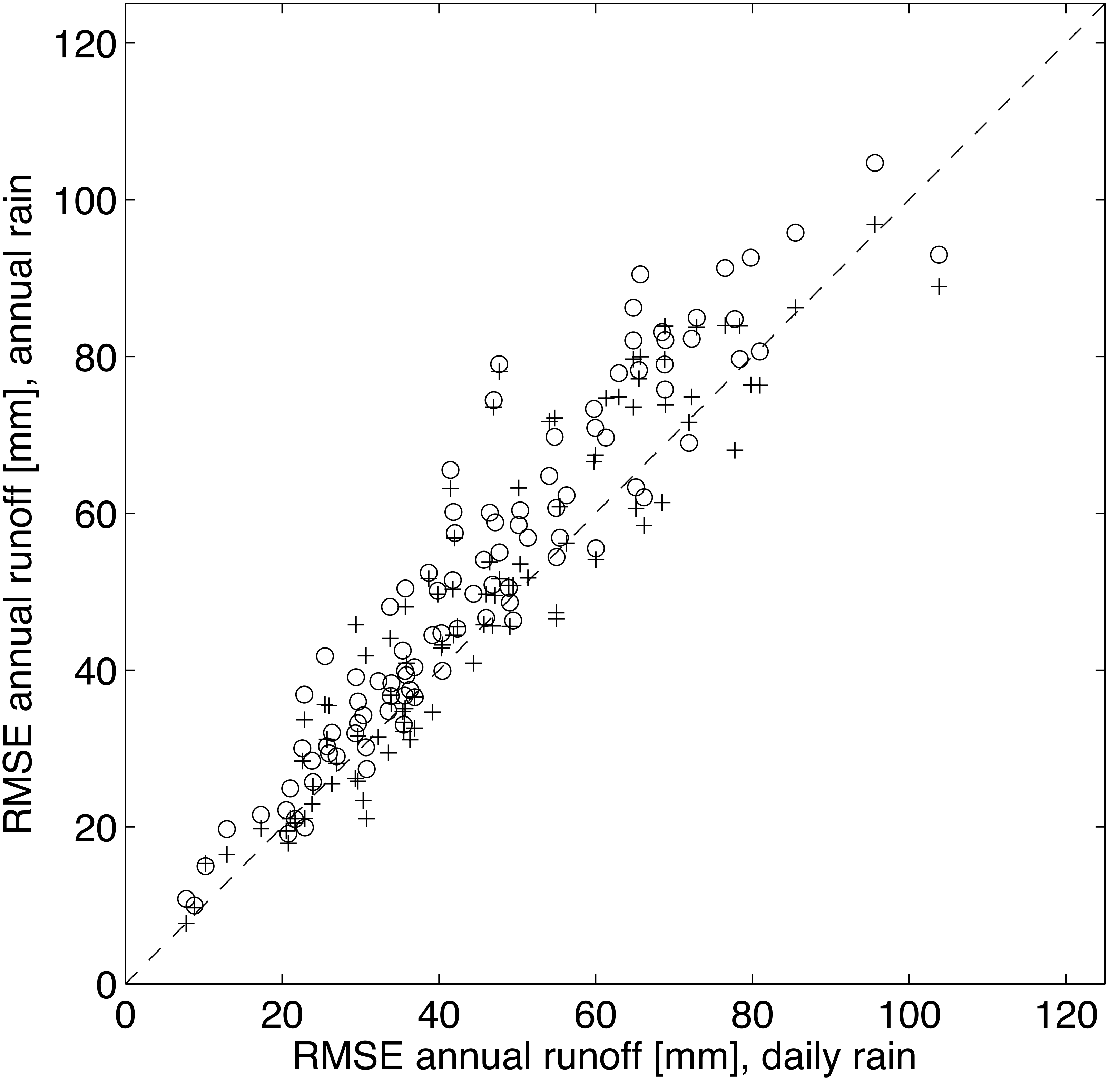

RMSE annual runoff [mm], annual rain
RMSE annual runoff [mm], daily rain
0
20
40
60
80
100
120

Table A1. Watersheds removed from analyses.

Gaging station	Reason for removal
03 02108000 NE Cape Fear, NC	Area and elevation in basin_characteristics file do not match U.S. Geolgoical Survey website or information in gage information file
03 02310947 Withlacoochee River near Cumpressco, FL	Multiple, long, discontinuous gaps in the streamflow record
03 02381600 Fausett Creek near Talking Rock, GA	Average streamflow from daily values, q is greater than 150% of reported average streamflow, Q
05 03357350 Plum Creek near Bainbridge, IN	Average streamflow from daily values, q, is less than 50% of reported average streamflow, Q
09 05062500 Wild Rice River at Twin Valley, MN	Average streamflow from daily values, q is greater than 150% of reported average streamflow, Q
09 05087500 Middle River at Argyle, MN	Average streamflow from daily values, q is greater than 150% of reported average streamflow, Q
09 05120500 Wintering River near Karlsruhe, ND	Average streamflow from daily values, q, is less than 50% of reported average streamflow, Q
10 06468250 James River near Kensal, ND	Average streamflow from daily values, q, is less than 50% of reported average streamflow, Q
10 06441500 Bad River near Fort Pierre, SD	Multiple long gaps in streamflow record
11 07067000 Current River at Van Buren, MO	Area and elevation in basin_characteristics file do not match U.S. Geological Survey website or information in gage information file
12 08079600 Brazos River at Justiceburg, TX	Average streamflow from daily values, q, is less than 50% of reported average streamflow, Q
15 09484000 Sabino Creek near Tucson, AZ	Multiple extended gaps in streamflow record throughout
15 09492400 East Fork White River near Apache, AZ	Average streamflow from daily values, q is greater than 150% of reported average streamflow, Q
16 10166430 West Canyon Creek near Cedar Fort, UT	Average streamflow from daily values, q, is less than 50% of reported average streamflow, Q
16 10172700 Vernon Creek near Vernon, UT	Average streamflow from daily values, q, is less than 50% of reported average streamflow, Q
16 10172800 South Willow Creek near Grantsville, UT	Average streamflow from daily values, q, is less than 50% of reported average streamflow, Q
16 10242000 Coal Creek near Cedar City, UT	Average streamflow from daily values, q, is less than 50% of reported average streamflow, Q
16 10249300 South Twin River nr Round Mountain, NV	Average streamflow from daily values, q, is less than 50% of reported average streamflow, Q
18 10259200 Deep Creek near Palm Desert, CA	Average streamflow from daily values, q, is less than 50% of reported average streamflow, Q
18 10263500 Big Rock Creek near Valyermo, CA	Average streamflow from daily values, q, is less than 50% of reported average streamflow, Q
18 11253310	Average streamflow from daily values, q, is less

Cantua Creek near Cantua Creek, CA	than 50% of reported average streamflow, Q
17 12040500 Queets River nr Clearwater, WA	Runoff ratio is greater than 1; q is greater than p
17 12041200 Hoh River nr Forks, WA	Runoff ratio is greater than 1; q is greater than p
17 12056500 NF Skokomish River near Hoodsport, WA	Runoff ratio is greater than 1; q is greater than p
17 12147500 NF Tolt River near Carnation, WA	Runoff ratio is greater than 1; q is greater than p and Q is greater than P
17 12147600 SF Tolt River near Index, WA	Runoff ratio greater than 1; Q is greater than P
17 12167000 NF Stillaguamish River near Arlington, WA	Runoff ratio greater than 1; q is greater than p and Q is greater than P
17 12186000 Sauk River near Darrington, WA	Runoff ratio greater than 1; q is greater than p and Q is greater than P
17 14158500 McKenzie River near Clear Lake, OR	Runoff ratio greater than 1; q is greater than p
17 14400000 Brookings, OR	Runoff ratio greater than 1; q is greater than p and Q is greater than P

Table A2. Modified streamflow records.

Gaging station	Issue	Resolution
03 02051000 North Meherrin River near Lunenburg, VA	Gap in streamflow record from 10/1/1980 through 9/30/1981	Use streamflow from 10/1/1981 through 12/31/2010
03 02235200 Blackwater Creek near Cassia, FL	Large gaps in streamflow record from 12/1/1980 through 6/9/1985	Use streamflow from 7/1/1985 through 12/31/2010
03 02408540 Hatchet Creek below Rockford, AL	Gap in streamflow record from 9/25/1980 through 9/30/1980	Use streamflow from 10/1/1980 through 12/31/2010
03 02464146 Turkey Creek near Tuscaloosa, AL	Gap in streamflow record from 10/1/1984 through 9/30/1986; recorded as zeroes	Use streamflow from 10/1/1986 through 12/31/2010 only
05 03066000 Blackwater River at Davis, WV	Gap in streamflow record from 10/1/1991 through 9/30/1992	Use streamflow from 10/1/1992 through 12/31/2010 only
05 03159540 Shade River near Chester, OH	Some estimated streamflow; no significant gaps found	Use data as are
05 03161000 South Fork New River	Some estimated streamflow; no significant gaps found	Use data as are

near Jefferson, NC		
05 03187500 Cranberry Creek near Richmond, WV	Gap in streamflow record from 10/1/1982 through 2/29/1984	Use streamflow from 3/1/1984 through 12/31/2010 only
05 03281100 Goose Creek at Manchester, KY	Gap in streamflow record from 10/1/2000 through 9/30/2001 and 10/1/2003 through 9/30/2006	Use streamflow from 1/1/980 through 9/30/2000 only
05 03300400 Beech Fork at Maud, KY	Gap in streamflow record from 5/3/2010 through 6/13/2010	Use streamflow from 1/1/1980 through 4/30/2010 only
06 03450000 Beetree Creek near Swannanoa, NC	Gap in streamflow record from 10/1/1981 through 8/28/1985	Use streamflow from 9/1/1985 through 12/31/2010
09 05062500 Wild Rice River at Twin Valley, MN	Gap in streamflow record from 10/21/1983 through 9/13/1989	Use streamflow from 10/1/1989 through 12/31/2010
10 06037500 Madison River near West Yellowstone, MT	Gap in streamflow record from 10/1/1986 through 9/30/1988	Use streamflow from 10/1/1988 through 12/31/2010 only
10 06043500 Gallatin River near Gallatin Gateway, MT	Gap in streamflow record from 10/1/1981 through 9/30/1984	Use streamflow from 10/1/1984 through 12/31/2010 only
10 06188000 Lamar River near Tower Falls Ranger Station, Yellowstone National Park	Gap in streamflow record from 10/1/1985 through 4/30/1986 and from 10/1/1986 through 8/31/1988	Use streamflow from 9/1/1988 through 12/31/2010 only
08 07290650 Bayou Pierre near Willows, MS	Extended gaps in record between 10/1/2009 and 12/31/2010	Use streamflow from 1/1/1980 through 9/30/2009
08 07295000 Buffalo River near Woodville, MS	Extended gaps in record between 10/1/2009 through 12/31/2010	Use streamflow from 1/1/1980 through 9/30/2009
08 07376000 Tickfaw River at Holden, LA	Gap in streamflow record from 10/1/1988 through 9/30/1989	Use streamflow from 10/1/1989 through 12/31/2010 only
12 08025500 Bayou Toro near Toro, LA	Gap in streamflow record from 10/1/1986 through 9/30/1988	Use streamflow from 10/1/1988 through 12/31/2010 only
12 08155200 Barton Creek near Oak Hill, TX	Gap in streamflow record from 10/15/1982 through 1/29/1989; also multiple periods of zero streamflow	Use streamflow from 2/1/1989 through 12/31/2010
15 09497800 Cibecue Creek near Chysotile, AZ	Gap in streamflow record from 10/1/2009 through 6/13/2010	Use streamflow from 1/1/1980 through 9/30/2009 only
15 09505200	Gap in streamflow record from	Use streamflow from 10/1/1988

Wet Beaver Creek near Rimrock, AZ	10/1/1982 through 9/30/1985 and 10/1/1987 through 9/30/1988	through 12/31/2010 only
17 12025000 Newaukum River near Chehalis, WA	Gap in streamflow record from 10/1/1981 through 9/30/1982	Use streamflow from 10/1/1982 through 12/31/2010 only
17 12043000 Calawah River near Forks, WA	Gap in streamflow record from 10/1/1980 through 2/29/1984	Use streamflow from 3/1/1984 through 12/31/2010
17 12141300 Middle Fork Snoqualmie River near Tanner, WA	Gap in streamflow record from 10/1/1991 through 9/30/1992	Use streamflow from 10/1/1992 through 12/31/2010 only
17 12374250 Mill Creek near Niarada, MT	Gap in streamflow record from 9/1/1982 through 9/30/1982	Use streamflow from 10/1/1982 through 12/31/2010
17 13310700 South Fork Salmon River near Krassel Ranger Station, ID	Gap in streamflow record from 10/1/1982 through 3/31/1985, 10/1/1986 through 1/31/1989,	Use streamflow from 2/1/1989 through 12/31/2010