EVALUATION OF WATER BALANCE MODELS: AN ASSESSMENT IN MIXED CONIFER FORESTS OF ARIZONA

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Much of the surface water used in Arizona originates as precipitation, often snow, on the higher elevation watersheds. However, the surface water supplies from these watersheds are generally limited in most years, although it has been shown that multiple-resource management practices implemented on higher elevation watersheds can favorably affect subsequent streamflow and water quality characteristics (Rich 1972; Rich and Thompson 1974; Baker 1986; Gottfried 1991; Gottfried and Ffolliott 1992). A capability to predict the streamflow from higher elevation watersheds before and after the implementation of multiple-resource management practices using water balance models based on easily acquired information is needed. Such predictions would be helpful to managers in planning for the possibility of increased streamflow into the river systems of Arizona and, as a consequence, the availability of more water for downstream users.

One major objective of watershed research in Arizona has been, and continues to be, the validation of water balance models and, where appropriate, making modification of these models to better represent the measured parameters: annual streamflow totals, timing of streamflow regimes, and such. Results from previous investigations by Baker and Carder (1977), Baker and Rogers (1983), and Jeton (1990) show that many of the existing water balance models require some modifications—input variables, functions, coefficients—to simulate the actual conditions that have been measured.

This paper reports on a study to evaluate the accuracy of three water balance models in simulating annual streamflow totals from a watershed in the mixed conifer forests of Arizona. Comparisons have been made between observed and simulated streamflow before and after the implementation of a treatment designed to demonstrate and evaluate multiple-resource management practices in mixed conifer forests (Gottfried 1991). Future investigations will focus largely on analytical comparisons between observed and simulated hydrographs for the same watershed.

Study Area

The south fork of Thomas Creek, within the Apache–Sitgreaves National Forest in eastern Arizona, was the study area. This 562-acre watershed is situated in the headwater region of the Salt River. It is a main tributary of the Gila River and a main source of surface water for the Phoenix metropolitan area. The watershed is located between 8,400 and 9,200 feet in elevation. Soils are classified as Mollic Eutroboralfs and Mollic Cryoboralfs, and are derived from basaltic parent materials. Annual precipitation averages about 30 inches, with approximately 55 percent of this precipitation occurring as snowfall during the October through May winter precipitation period. Annual streamflow was nearly 3.2 inches prior to the treatment. About 80 percent of the annual streamflow total occurs during the snowmelt period of March, April, and May.

The watershed originally supported undisturbed, multistoried, old-growth stands of mixed conifer species (Gottfried 1991; Gottfried and Ffolliott 1992). These stands consisted of Douglas-fir (*Pseudotsuga menziesii* var. *glauca*), white fir (*Abies concolor*), corkbark fir (*A. lasiocarpa* var. *arizonica*), Engelmann spruce (*Picea engelmannii*), blue spruce (*P. pungens*), ponderosa pine (*Pinus ponderosa)*, southwestern white pine (*P. strobiformis*), and quaking aspen (*Populus tremuloides*). The pretreatment basal area of these stands was about 185 square feet per acre.

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The Treatment

Following a calibration period, the upper 75 percent of the watershed was harvested in 1978 according to single-tree selection, group selection, and small patch-cut prescriptions; the lower part of the watershed remained untreated, however, because of the steep slopes encountered. The timber harvest implemented resulted in a nearly 35 percent reduction in the basal area on the treated areas and the creation of 63 small openings representing about 13 percent of the watershed area. The treatment resulted in a significant increase in annual streamflow of almost 1.7 inches, an increment representing approximately 45 percent of the pretreatment streamflow (Gottfried 1991). The increases in streamflow were attributed largely to reduced evapotranspiration from the forest overstory and increased snow accumulations in the small openings.

Analysis

The results presented in this paper represent an analysis of the relative accuracies of the three water balance models in simulating annual streamflow totals from the south fork of Thomas Creek. Inputs to the models represented the conditions on the watershed at the initiation of the simulation exercises. In this initial phase of the study, outputs from the models, that is, the simulated annual streamflow totals, were compared to the corresponding streamflow records by a discrepancy ratio (DR) between the simulated and observed streamflow. The closer the DR value was to 1, the closer the simulated streamflow to the observed streamflow, and therefore the more accurate the model in simulating annual streamflow totals from the watershed. DR values less than 1 indicate that the simulated streamflow was less than the observed streamflow; in other words, the model being evaluated underestimated the observed streamflow. DR vales greater than 1 represented the reverse situation. The three water balance models evaluated were:

1. *The combined WATBAL–SNOWMELT simulation model*: WATBAL simulates the total water balance on an annual basis and compiles the results obtained from individual response units into a composite overview of a watershed; it emphasizes snow accumulation and melt processes (Leaf and Brink 1973). The original WATBAL simulation model assumed a continuous snowpack, a major constraint when applied in the southwestern United States, where snowpacks are generally intermittent. A modified snow component called SNOWMELT provides for modeling intermittent snowpack conditions within the WATBAL framework (Solomon et al. 1976).

2. *The Baker-Kovner streamflow regression model*: This nonlinear regression model predicts annual streamflow totals from inputs of precipitation, potential insolation, basal area of the forest overstory, and two interaction terms (precipitation–basal area and precipitation–potential insolation). The model was developed with data from the Beaver Creek watershed (Brown at al. 1974), and as a consequence is strictly applicable to watersheds with volcanic soils and climate similar to Beaver Creek. Testing of the usefulness of the model for other watershed conditions appeared justified in the opinion of the authors of this paper.

3. *The YIELD II simulation model*: YIELD II, a modification of the earlier YIELD simulation model, has two components: one that simulates streamflow in the winter and throughout the snowmelt season in the spring; and one that predicts streamflow from summer rainfall events (Ffolliott and Guertin 1988). A degree-day technique for estimating snowmelt is used in the simulation. Knowing the daily snowmelt and snowmelt runoff efficiency, that is, the ratio of total snowmelt on a watershed to the total amount of water released in the form of streamflow, allows simulation of the volume of water that leaves a watershed as streamflow. The second simulation component is largely a modification of the model developed by Rogerson (1976) to describe the hydrologic behavior of watersheds with snow-free conditions.

Simulations were made for 7 years that represent two periods: pretreatment conditions and post-treatment conditions. The four pretreatment years included 1 year of above-average (1973), 1 year of near-average (1975), and 2 years of below-average winter precipitation (1974 and 1977). The 3 post-treatment years represented 1 year of above-average (1985), 1 year of near-average (1980), and 1 year of below-average winter precipitation (1981).

Results and Discussion

Comparisons of observed and simulated annual streamflow totals and the corresponding DR values obtained for the WATBAL–SNOWMELT simulation model, the Baker-Kovner streamflow regression model, and the YIELD II simulation model are presented in Tables 1, 2, and 3, respectively.

The combined WATBAL–SNOWMELT simulation model generally overestimated the observed annual streamflow totals. The relative magnitude of the overestimations is seemingly unrelated to the amount of winter precipitation, which produces most of the streamflow from the watershed. That WATBAL–SNOWMELT overestimated most of the observed streamflow was not surprising, because Baker and Roger (1983) reported similar findings when applying this water balance model on the south fork of Thomas Creek in an earlier study. In fact, the average overestimation for the pretreatment conditions shown in Table 1 agrees closely with that reported by Baker and Rogers, whose study consisted largely of modeling the monthly streamflow for the pretreatment period of 1966 to 1970, rather than annual streamflow totals for later pretreatment periods. These authors also divided the south fork of Thomas Creek into four response units for simulation purposes, while only two response units were delineated in the current study. The average overestimation of WATBAL–SNOWMELT for post-treatment conditions was less than 10 percent. Regardless of whether pretreatment or post-treatment conditions are considered, however, it is felt that the problems that Baker and Roger identified with WATBAL–SNOWMELT also contributed to the overestimations found in this present study. For example, WATBAL–SNOWMELT melts snow too rapidly in the winter, particularly at the end of the melt period, which likely contributes to the overestimation of streamflow.

The accuracy of the Baker-Kovner streamflow regression model in predicting the observed annual streamflow totals on the south fork of Thomas Creek appears related to the amount of winter precipitation in most years of the study. Considering pretreatment and post-treatment periods collectively, as there were few meaningful differences in the average DR values between the two periods, a close agreement was found between the observed and simulated streamflow in the years of near-average winter precipitation (1975 and 1980). However, the model underestimated the streamflow in the years of above-average winter precipitation (1973 and 1985), while it overestimated the annual streamflow

Table 1. Observed and simulated annual streamflow totals, and the corresponding DR values for the combined WATBAL–SNOWMELT simulation model (in inches).

Year	Observed	Simulated	DR
Pre-treatment conditions			
1973	14.25	19.66	1.38
1974	0.12	1.32	11.00
1975	5.52	8.52	1.54
1977	0.56	0.55	0.98
Mean	5.11	7.51	1.47
Post-treatment conditions			
1980	8.53	9.68	1.13
1981	1.50	2.09	1.39
1985	11.65	11.96	1.03
Mean	7.23	7.91	1.09

Table 2. Observed and simulated annual streamflow totals, and the corresponding DR values for the Baker-Kovner streamflow regression model (in inches).

Year	Observed	Simulated	DR
Pre-treatment conditions			
1973	14.25	10.43	0.73
1974	0.12	0.33	2.75
1975	5.52	5.50	1.00
1977	0.56	1.01	1.80
Mean	5.11	4.32	0.85
Post-treatment conditions			
1980	8.53	8.23	0.96
1981	1.50	1.32	0.88
1985	11.65	8.65	0.74
Mean	7.23	6.07	0.84

Table 3. Observed and simulated annual streamflow totals, and the corresponding DR values for the YIELD II simulation model (in inches).

Year	Observed	Simulated	DR
Pre-treatment conditions			
1973	14.25	9.44	0.66
1974	0.12	0.11	0.92
1975	5.52	3.35	0.61
1977	0.56	0.28	0.50
Mean	5.11	3.30	0.65
Post-treatment conditions			
1980	8.53	7.49	0.88
1981	1.50	1.32	0.88
1985	11.65	6.22	0.53
Mean	7.23	5.01	0.69

totals in 2 (1974 and 1977) of the 3 years when the winter precipitation was below average. Whether the results obtained with the Baker-Kovner model are reflective of the actual conditions encountered on the south fork of Thomas Creek or an aberration of the data is unknown. The relative contributions of the respective terms, and particularly the interaction terms in the regression formulation of the model, are difficult to evaluate individually because of the structure of the model.

The YIELD II underestimated the observed annual streamflow totals on the south fork of Thomas Creek in all of the years evaluated. Of the three water balance models evaluated, YIELD II also produced the most consistent results in terms of the DR values obtained, especially in the post-treatment period. The reasons for the consistent underestimations can only be speculated upon at this time. Due to the large proportion of the annual streamflow occurring during the snowmelt period in the winter and spring, the problem probably lies within the component of YIELD II that simulates streamflow in these two periods. The baseline temperature at which snowmelt is initiated in the degree-day technique for estimating snowmelt might be too low. Therefore, adjustments in this baseline temperature may be needed to "allow" a greater volume of snowmelt to take place. Additional study of the snowmelt processes in the mixed conifer forests of Arizona is required before making this adjustment, however. Snowmelt runoff efficiency, the other primary input to the model, represents a measured parameter of the conditions being simulated, and should probably not be modified in the routing procedure for simulating the volume of water that leaves the watershed.

Modifications are likely needed in all of the water balance models evaluated to more accurately and consistently simulate the annual streamflow totals from the mixed conifer forests represented on the south fork of Thomas Creek. The combined WATBAL–SNOWMELT model still appears to be unable to adequately simulate the intermittent snowpack conditions found in the southwestern U.S. In reference to the Baker-Kovner streamflow regression model, the average basal areas and precipitation amounts on the south fork of Thomas Creek are both higher than those found on Beaver Creek. It is likely, therefore, that a wider range of input data is needed to derive a set of regression coefficients that better simulates the conditions encountered on the south fork of Thomas Creek. The component of YIELD II that simulates streamflow in the winter and throughout the snowmelt season in the spring needs to be further evaluated to determine whether the degree-day technique for estimating snowmelt and the procedure for routing snowmelt water off of a watershed are appropriate to the conditions being simulated. It is anticipated that future comparisons between the observed and simulated hydrographs can provide insight on the nature of these modification in the water balance models.

Conclusions

Water balance models that are sensitive to climatic variability and the impacts of watershed management activities are necessary to plan and implement efficient water management practices. However, this and related investigations have shown that the existing water balance models generally require modifications in their formulations to simulate streamflow regimes before they become suitable for operational use—in this case, within the mixed conifer forests of Arizona. Such a conclusion should be expected, because the water balance models studied are largely deterministic in structure, and therefore must be modified before they are applied to local conditions. Nevertheless, the evaluations of water balance models presented in this and earlier papers should be helpful to managers in judging the relative value of the models is simulating particular hydrologic situations. Furthermore, these evaluations are useful in deciding which of the models, if any, warrant further testing and refinement.

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