APPLICATION OF XTOP_PRMS MODEL IN GREEN LAKES VALLEY, COLORADO FRONT RANGE: RUNOFF SIMULATION AND FLOWPATH IDENTIFICATION

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ABSTRACT

Stream runoff was simulated from 1996 to 2000 using XTOP_PRMS (coupling of TOPMODEL and Precipitation Runoff Modeling System) model under Modular Modeling System at Martinelli and Green Lake 4 catchments in Green Lakes Valley, Colorado Front Range. Two flowpaths determined by XTOP_PRMS model, surface flow (infiltration-excess overland flow) and subsurface flow, were compared against the flowpaths determined by mixing model using isotopic and chemical tracers. Three tracers (DOC, K/Si, and $\delta^{18}O$) were used in mixing model to identify four flowpaths, i.e., overland, upper soil horizon, lower soil horizon, and base flow. The results showed that the runoff simulation using XTOP_PRMS model is reasonably successful for Martinelli catchment (8 ha in drainage area). The Nash-Sutcliffe efficiency is 0.76. The t-test of two means for paired sample showed that the difference between the observed and modeled runoff was not significantly different at α=0.05 at Martinelli catchment (n = 1611, p = 0.6). The flowpaths identified by XTOP_PRMS model matched the flowpaths determined by the tracer-mixing model reasonably well in magnitude, but poorly in pattern. The surface flow primarily occurred in the beginning of snowmelt at Martinelli as illustrated by the tracer-mixing model. Both runoff simulation and flowpath identification using XTOP_PRMS model were relatively poor at Green Lake 4 catchment, which has a drainage area of 220 ha. The runoff peaks observed in May and June were not captured in runoff simulation. The problem may be caused by poor understanding of behaviors of flowpath parameters and insensitivity of snowmelt to daily mean air temperature.

INTRODUCTION

Identification of flow sources and pathways is crucial in understanding the links between terrestrial and aquatic ecosystems (Cirmo and McDonnell, 1997; Holko and Lepisto, 1997). One of features of recent progress in hydrological modelling to understand the flow paths has been the more widespread availability of digital elevation models and the integration of hydrological modelling with geographical information systems (Beven, 2000). TOPMODEL (TOPography based hydrological MODEL), now over 20 years old, provides one of the few easy to use model structures that can make use of digital elevation model (DEM) (Beven, 1997). The number of applications of the TOPMODEL has recently increased in simulating stream discharge and identifying flowpaths in small (several km^2) to large (thousands of km^2) catchments (e.g., Holko and Lepisto, 1997; Guntner *et al.*, 1999; Franchini *et al.*, 1996). The advantages of TOPMODEL primarily include its open model structure and simplicity in dealing with complex terrain (Beven, 1997). However, TOPMODEL has not been applied to seasonally snow-covered alpine catchments in the western United States. The drawback is that this model is not efficient in modeling snow-dominated catchments not only because it lacks a module routine to calculate snowmelt but also because this model is not designed to handle temporal and spatial variation of snow distribution and snow water equivalent. Recently, efforts have been made to incorporate TOPMODEL with other models such as Precipitation Runoff Modeling System (PRMS) to deal with snowmelt component (Leavesley *et al.*, 1998; 2002; also see web site at http://wwwbrr.cr.usgs.gov/mms).

Here we report an application of the XTOP_PRMS (integration of TOPMODEL and PRMS) model to seasonally snow-covered alpine basins in Green Lakes Valley, Colorado Front Range. Purposes of this study are: (1) to test the applicability of the XTOP_PRMS model for runoff simulation in seasonally snow-covered alpine catchments; (2) to understand flowpaths determined by the XTOP_PRMS model and (3) to validate the flowpaths by comparing them with the flowpaths determined by tracer-mixing model.

SITE DESCRIPTION

Green Lakes Valley (40°03' N, 105°35' W), located in Colorado Front Range and entirely within the Arapaho-Roosevelt National Forest, is an east-facing headwater catchment that abuts the Continental Divide (Figure 1). The

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basin is 700 ha in area and ranges in elevation from 3250m to ~4000m. The catchment appears typical of the high-elevation environment of the Colorado Front Range. Climate is characterized by long, cool winters and a short growing season (1-3 months). Since 1951, mean annual temperature is –3.8°C, and annual precipitation is about 1000 mm (Williams *et al.*, 1996). About 80% of the annual precipitation occurred as snow. Stream flow was markedly seasonal, varying from <0.05 m^3s^{-1} during the winter months to >3.0 m^3s^{-1} at maximum discharge during snowmelt at the lower end of the valley (Williams *et al.*, 2001).

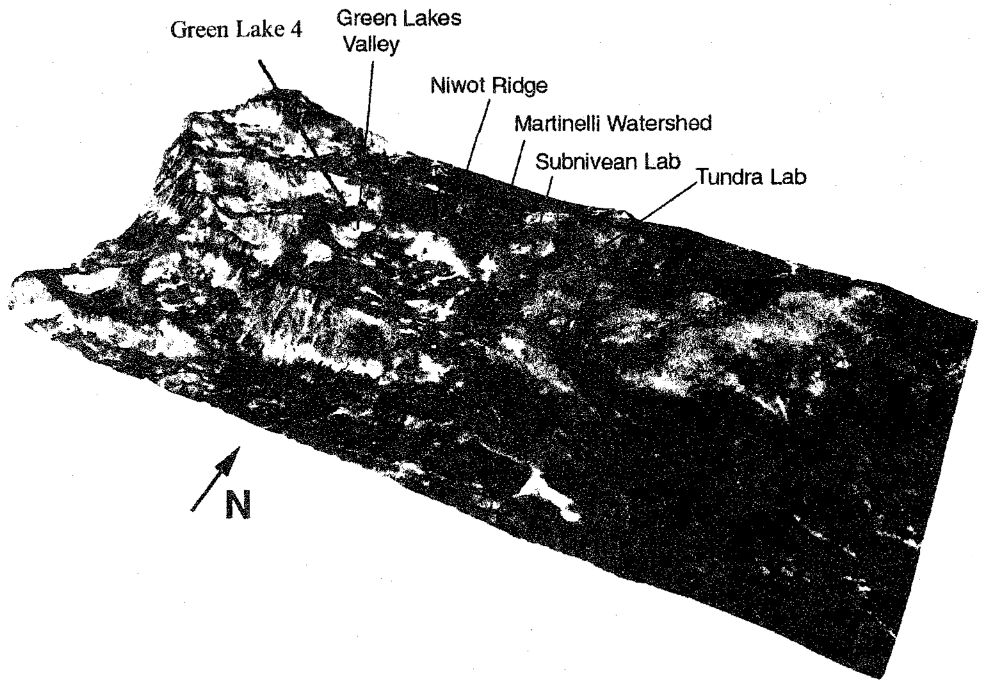

Figure 1 Location map showing the Martinelli and Green Lake 4 catchments

This study focuses on Martinelli drainage basin and Green Lake 4 drainage basin (Figure 1). The Martinelli basin is located on the south slope of Niwot Ridge, with an area of 8 ha and elevation ranges from 3415 m to ~3800 m. Snow cover accumulates from wind drifting which generally exceeds 10 m in May, the end of the accumulation season. The Green Lake 4 basin has an area of 220 ha and ranges in elevation from 3550 m at the outflow to ~4000 m. The Green Lake 4 basin is almost entirely alpine in nature (Caine, 1995). Daily discharge measurements have been maintained from late April to late October at the Martinelli basin since 1981 and at Green Lake 4 outlet since 1982.

Stream water and zero-tension soil lysimeters were sampled at the Martinelli and Green Lake 4 catchments in 1996. Snowmelt was sampled at the nearby Subnivean laboratory in 1996. Samples were analyzed for major solutes, DOC, and water $\delta^{18}O$. Procedures of sampling and sample analyses can be found elsewhere (Williams *et al.*, 2001).

METHODS

XTOP_PRMS Model

XTOP_PRMS model is an integration of TOPMODEL (Beven, 1997; 2000) and precipitation-runoff modelling system (PRMS) (Leavesley, 1983). It is developed by USGS Water Resources Division in Denver (Leavesley *et al.*, 1998; 2002; Webb et al., manuscript, 2002; also see web site of Modular Modeling System at http://wwwbrr.cr.usgs.gov/mms) and used to understand mechanism of flow generation and identify flow pathways. It is currently ported into the Modular Modelling System (MMS) (Leavesley *et al.*, 1996; 1998; 2002), which provides the research and operational framework needed to support development, testing, and evaluation of physical-process algorithms, and to facilitate integration of user-selected sets of algorithms into operational physical-process models. Snowmelt computational routine is Hydro-17, a temperature index module developed by NOAA.

TOPMODEL is not a single model structure that will be of general applicability, but more a set of conceptual tools that can be used to simulate hydrological processes in a relatively simple way, particularly the dynamics of surface or subsurface contributing areas (Beven, 1997). The simplicity of the model comes from the use of the topographic index, $\ln(a/\tan\beta)$ (Kirkby, 1975), or the soil-topographic index, $\ln(a/T_0 \tan\beta)$ (Beven, 1986), where a is the area draining through a point from upslope (L^2), β is the local slope angle (tanβ is then the local slope gradient), and T_0 is the saturated lateral (horizontal) transmissivity of soil ($L^2\ T^{-1}$). This index is used as an index of hydrological similarity. All points with the same value of the index are assumed to respond in a hydrological similar way. High index values will trend to saturate first and will therefore indicate potential subsurface or surface contributing areas. The expansion and contraction of such areas as the catchment wets and dries is then indicated by the pattern of the index (Beven, 2000; Holko and Lepisto, 1997).

Model Validation

The discharge predicted by the model is evaluated by Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970) as expressed below:

$$E = 1.0 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - O_{mean})^2}$$

where P is the predicted value, O is the observed value, O_{mean} is the mean observed value, and i is the observation number. The ideal value for Nash-Sutcliffe efficiency is one. If it is less than one, the closer the better. For a daily comparison between observed and modeled discharges, a t-test for two means of paired samples is also used to examine if their means are significantly different or not at a given significance level. Also, modeled flowpaths were compared against hydrograph separation using isotopic and chemical tracers.

Both traditional mass balance mixing model and end-member mixing analysis (EMMA) (Christophersen and Hooper, 1992) were used to separate hydrograph. EMMA and principal component analysis (PCA) technique were used to identify conservative tracers and number of components (end-members) contributing to the stream flow. Characterization of components (end-members) was verified by PCA projection into U space. Ratio of K/Si was demonstrated to be an indicator of rapid shallow flow (Elsenbeer *et al.*, 1995). DOC was used to characterize the upper soil horizon (organic horizon) flow (Brown *et al.*, 1999), and $\delta^{18}O$ to identify base flow. Finally, four flow paths were identified, including overland flow, upper soil horizon flow, lower soil horizon flow, and base flow.

RESULTS AND DISCUSSIONS

Runoff Simulation

Input data for running XTOP_PRMS model include precipitation, temperature, solar radiation, and pan evaporation, all at daily basis. Since pan evaporation data were not available at Green Lakes Valley, these data were automatically calculated by the model based on temperature and estimated humidity. Outputs primarily include modeled discharge, evapotranspiration from root zone, snow sublimation, snowmelt, and storage changes in unsaturated zone and saturated zone. Discharges were partitioned into two flowpaths, i.e., infiltration-excess overland flow (surface flow as named in this study) and subsurface flow.

Incident precipitation events occurred throughout the year (Figure 2, upper panel). Snow started accumulating in late fall and generally attained its maximum accumulation in mid or late April. Both the maximum and minimum daily air temperature were above 0 °C primarily from late spring to early fall (Figure 2, middle and lower panel). Intensive snowmelt events generally occurred from late spring to summer as a result of the abrupt rise in air temperature as shown by the modeled snowmelt (Figure 3 and 4, upper panel). The stream runoff at both the Martinelli and the Green Lake 4 catchments was thus dominated by those snowmelt events with a single large peak as shown by the observed and modeled runoff (Figure 3 and 4, lower panel).

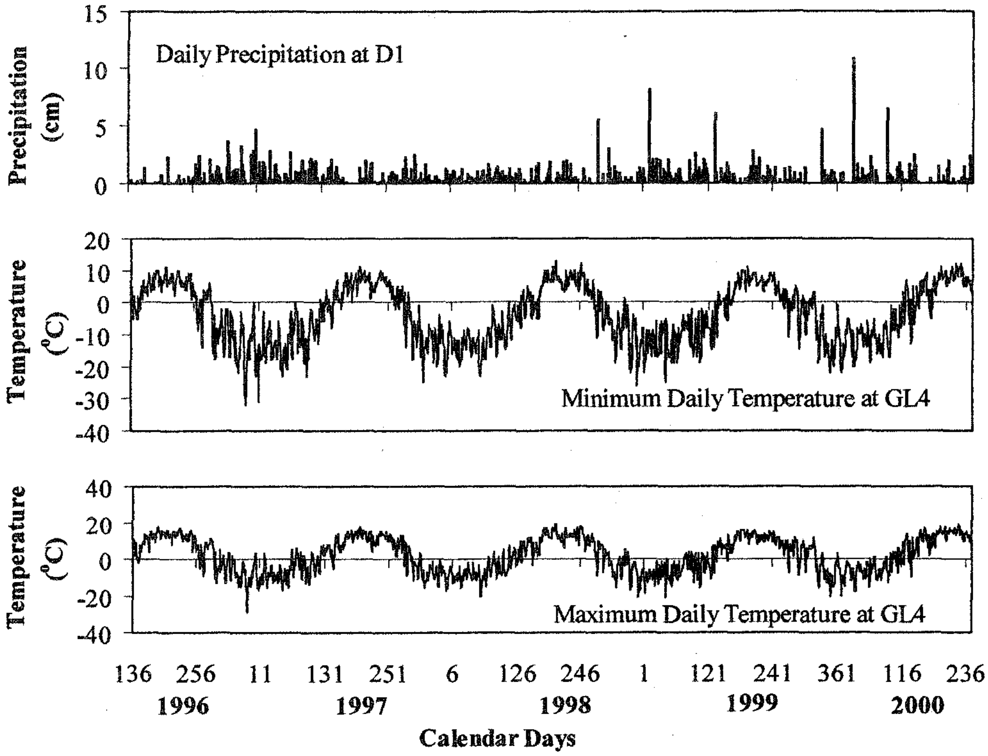

Figure 2 Time-series of input data sets from 1996 to 2000, including daily precipitation at D1 (upper panel), minimum daily air temperature at Green Lake 4 (middle panel), and maximum daily air temperature at Green Lake 4 (lower panel)

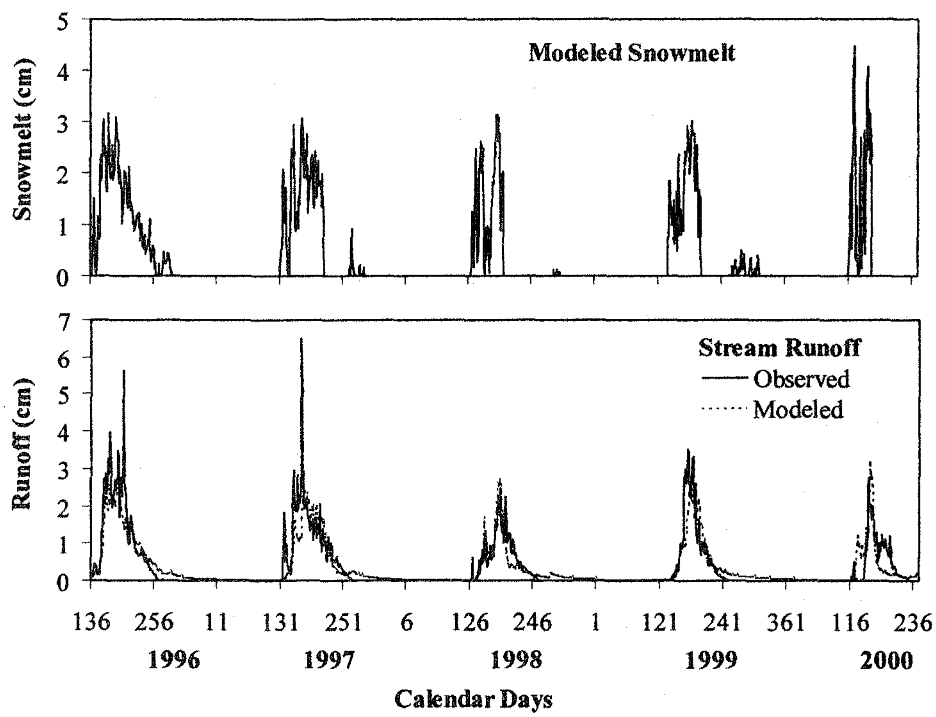

Figure 3 Simulated daily snowmelt (upper panel) and simulated and observed daily runoff (lower panel) from 1996 to 2000 at Martinelli catchment

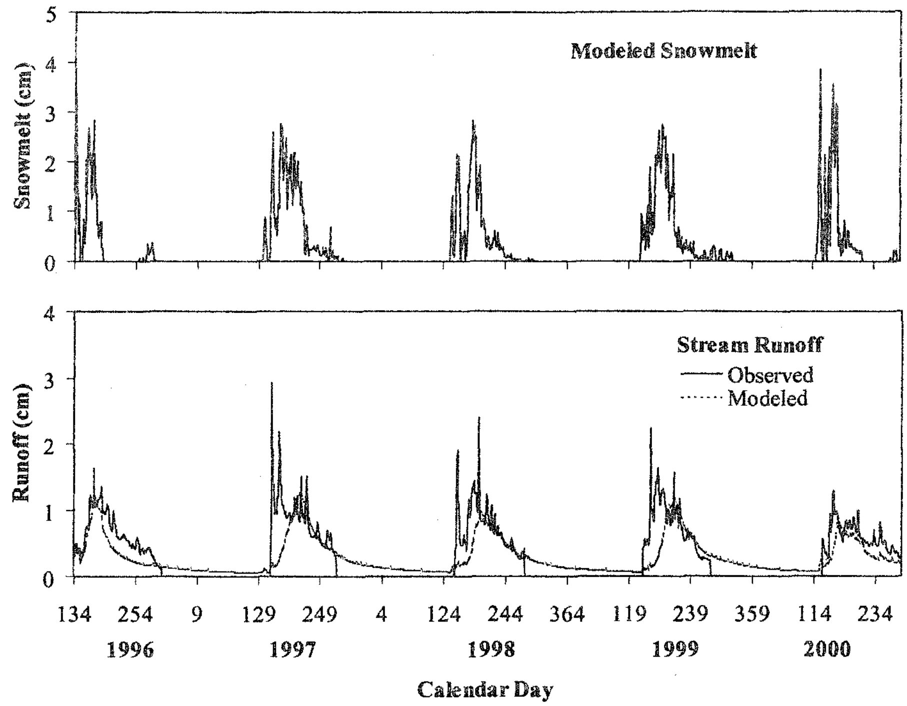

Figure 4 Simulated daily snowmelt (upper panel) and simulated and observed daily runoff (lower panel) from 1996 to 2000 at Green Lake 4 catchment

The modeled discharge was compared with the observed discharge based on two factors, i.e., the Nash-Sutcliffe efficiency and p value from t-test for two means of paired sample. The Nash-Sutcliffe efficiency is 0.76 for Martinelli catchment and 0.54 for Green Lake 4 catchment. Those values are lower than the ideal efficiency value of 1, indicating that the mean of the modeled runoff is lower than the mean of the observed runoff. This problem may be mainly caused by failure in capture of the isolated runoff peaks in runoff simulation, which have very high magnitudes and should modify the modeled mean at a large extent. The t-test of two means for paired sample showed that the difference between the observed and modeled runoff was not significantly different at $\alpha = 0.05$ at Martinelli catchment ($n = 1611$, $p = 0.6$), but significantly different at Green Lake 4 catchment ($n = 1600$, $p = 0.002$). In combining the Nash-Sutcliffe efficiency and the t-test, it is suggested that the modeled runoff matched the observed runoff reasonably well at Martinelli, except for the isolated peaks.

Water Budgets

Figure 5 shows monthly variations of water budget components for both Martinelli (upper panel) and Green Lake 4 (lower panel) catchments. Water changes in storage of saturated and unsaturated zone are expressed to have positive and negative signs. Positive sign denotes water gain from the hydrological system (mainly infiltration of snowmelt), while negative sign indicates water contribution from the saturated and unsaturated zone to channel system or/and evapotranspiration. It is seen that the evapotranspiration behaved in a similar seasonal pattern each year, with a peak around June and a magnitude of ca. 4.5 cm per month. A certain amount of snowmelt infiltrated through soils and stored in soils to increase soil storage during May and June according to the modeled snowmelt and runoff. This explains why the model missed the runoff peaks during this period. As a matter of fact, however, this is not the reality. The reality is that one or several runoff peaks was observed around mid-May each year and even the peak was the highest over the entire year, particularly at Green Lake 4 catchment (Figure 4). There might be two reasons that cause this problem. The first reason may be due to the hydro-17 snowmelt module. The hydro-17 is a temperature index snowmelt module using daily mean air temperature to calculate snowmelt. Drastic changes of air temperature within hours may dramatically alter snowmelt amount but, if daily mean air temperature is used, these changes may not be correctly simulated. The second reason may be from flowpath parameters. The parameters were calibrated using all the 1996 data, including both rising and receding limbs. Flowpath parameters may have heterogeneous nature and behave differently at different runoff stages. To consolidate this issue, however, future work is needed to understand behaviors of major flowpath parameters.

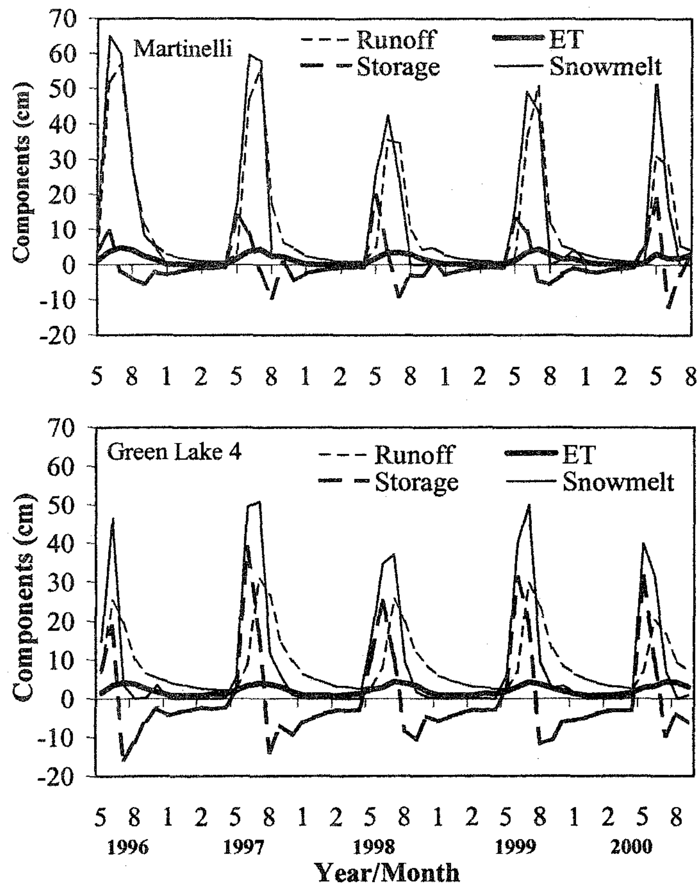

Figure 5 Monthly variation of simulated water balance components from 1996 to 2000 at Martinelli catchment (upper panel) and at Green Lake 4 catchment (lower panel)

Using three tracers (DOC, K/Si, and $\delta^{18}O$), we successfully identified four flowpaths at Martinelli and Green Lake 4 catchments for 1996. The four flowpaths at Martinelli basin in 1996 were at average overland flow (2%), upper soil horizon flow (16%), lower soil horizon flow (77%), and base flow (5%). The four flowpaths at Green Lake 4 basin in 1996 were at average overland flow (2%), upper soil horizon flow (23%), lower soil horizon flow (40%), and base flow (35%). The four flowpaths identified by the tracer-mixing model were re-categorized to approximately meet the two flowpaths identified by the XTOP_PRMS model, i.e., surface and subsurface flowpaths. The overland flow and upper soil horizon flow in the tracer-mixing model are realized to be equivalent of the surface flow in the XTOP_PRMS model, while the lower soil horizon flow and base flow are realized to be equivalent of the subsurface flow. Comparison of the two flowpaths (surface vs. subsurface) identified by the tracer-mixing model and the XTOP_PRMS model may be useful to evaluate how well the flowpaths were simulated by XTOP_PRMS model. The XTOP_PRMS model showed that the annual surface flow accounted for 24% and the annual subsurface flow comprised of 76% at Martinelli in 1996 (Figure 6), which were close to percentages determined by the tracer-mixing model (surface flow 18% and subsurface flow 82%). However, the surface flow was primarily occurred during the beginning 30 days as illustrated by the tracer-mixing model. The high proportion of surface flow determined by the XTOP_PRMS model mainly occurred during high flow period. For Green Lake 4 in 1996 (Figure 7), the surface flow determined by XTOP_PRMS model (6%) was much less than that determined by the tracer-mixing model (25%), suggesting that the surface flow was underestimated by XTOP_PRMS model.

CONCLUSIONS

The runoff simulation using XTOP_PRMS model is reasonably successful for the Martinelli catchment. The Nash-Sutcliffe efficiency is 0.76. The modeled runoff and the observed runoff are not significantly different from 1996 to 2000 at Martinelli basin ($n = 1611$, $p = 0.6$). The flowpaths identified by XTOP_PRMS model in 1996 matched the flowpaths determined by the tracer-mixing model reasonably well in magnitude, but poorly in pattern. The surface flow primarily occurred in the beginning of snowmelt at Martinelli as illustrated by the tracer-mixing model.

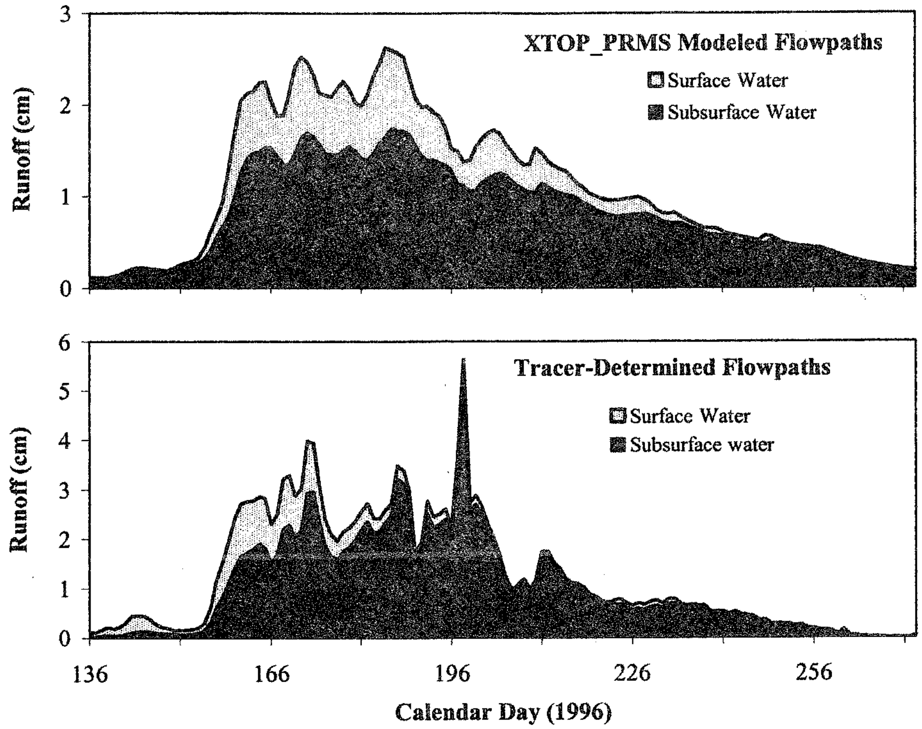

Figure 6 Daily variation of surface and subsurface flow in 1996 at Martinelli catchment for XTOP_PRMS modeled flowpaths (upper panel) and for tracer-mixing modeled flowpaths (lower panel)

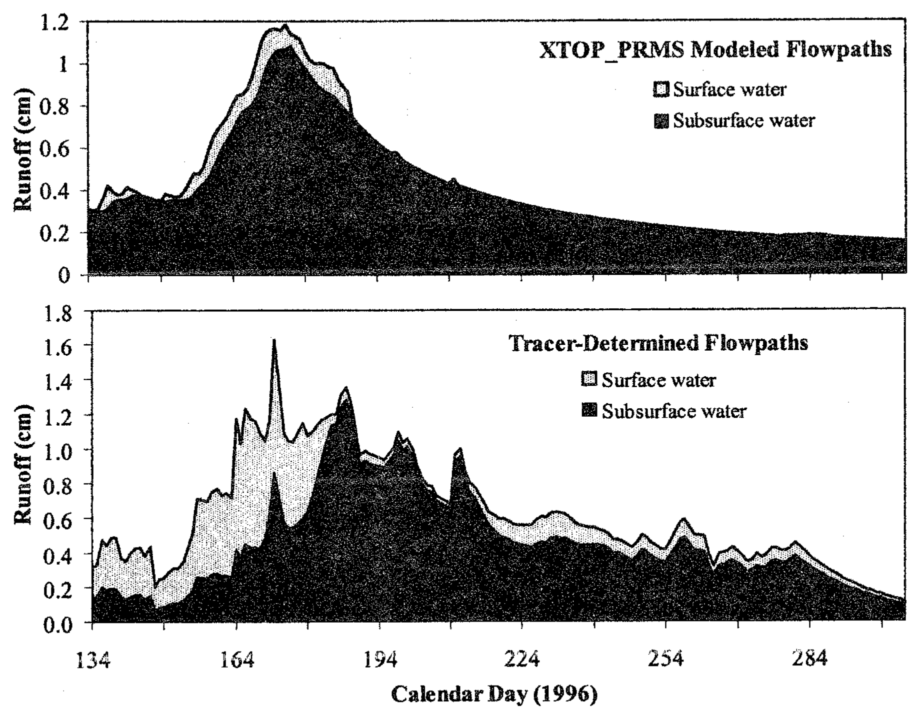

Figure 7 Daily variation of surface and subsurface flow in 1996 at Green Lake 4 catchment for XTOP_PRMS modeled flowpaths (upper panel) and for tracer-mixing modeled flowpaths (lower panel)

Both runoff simulation and flowpath identification using XTOP_PRMS model were relatively poor at the 220 ha Green Lake 4 catchment. The runoff peaks observed in May and June were not captured in runoff simulation. This problem may be caused by insensitivity of snowmelt to daily mean air temperature as used by hydro-17 snowmelt module and heterogeneous behaviors of flowpath parameters. Future work is needed to substitute the hydro-17 module with an hourly time step snowmelt module such as Mass and Energy Balance Model for Snow and Soil (SNTHERM) (Jordan, 1991) and to better understand behaviors of flowpath parameters at different runoff stages.

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