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# Simulated watershed responses to land cover changes using the Regional Hydro-Ecological Simulation System

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## Abstract:

In this work, we used the Regional Hydro-Ecological Simulation System (RHESSys) model to examine runoff sensitivity to land cover changes in a mountain environment. Two independent experiments were evaluated where we conducted simulations with multiple vegetation cover changes that include conversion to grass, no vegetation cover and deciduous/coniferous cover scenarios. The model experiments were performed at two hillslopes within the Weber River near Oakley, Utah watershed (USGS gauge # 10128500). Daily precipitation, air temperature and wind speed data as well as spatial data that include a digital elevation model with 30 m grid resolution, soil texture map and vegetation and land use maps were processed to drive RHESSys simulations. Observed runoff data at the watershed outlet were used for calibration and verification. Our runoff sensitivity results suggest that during winter, reduced leaf area index (LAI) decreases canopy interception resulting in increased snow accumulations and hence snow available for runoff during the early spring melt season. Increased LAI during the spring melt season tends to delay the snow melting process. This delay in snow melting process is due to reduced radiation beneath high LAI surfaces relative to low LAI surfaces. The model results suggest that annual runoff yield after removing deciduous vegetation is on average about 7% higher than with deciduous vegetation cover, while annual runoff yield after removing coniferous vegetation is on average as about 2% higher than that produced with coniferous vegetation cover. These simulations thus help quantify the sensitivity of water yield to vegetation change. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS runoff sensitivity; land cover change; RHESSys; leaf area index (LAI)

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## INTRODUCTION

The hydrology of the western USA mountains is mainly dominated by snowmelt. Precipitation in these snowmelt-dominated watersheds is stored in the form of snow, lost due to evaporation, sublimation and transpiration, or released as snowmelt driven runoff or infiltrated to groundwater that sustains baseflow.

A National Research Council (2008) report presented the current understanding of forest hydrology, connections between forest management and attendant hydrologic effects and suggested directions for future research to sustainably manage water resources from forested landscapes. The report called for future research in forest hydrology to move from principles to prediction. This call to move from principles to prediction is because the science community needs to understand the indirect and interacting hydrologic responses to changes in forested landscapes associated with climate change, forest disturbances, forest species composition and structure, land development and ownership and how these changes will affect water quantity and quality downstream and over long time scales.

Notable among paired watershed studies in the intermountain Rocky Mountain region are Wagon Wheel Gap, Fool Creek, Deadhorse Creek and Fraser Experimental Forest in central Colorado (Bates and Henry, 1928; Troendle and King, 1985, 1987; Van Haveren, 1988; Troendle and Olsen, 1994; Troendle and Reuss, 1997). The main categories of paired studies are afforestation, deforestation, re-growth and forest conversion experiments. These field experiments quantify the consequences of land use changes on runoff, flood and low flow response and water quality.

Meeting water supply needs is becoming more difficult because elevated water demand is occurring simultaneously with changes in climate, human population growth and development and land use. Therefore, understanding the hydrologic effects of land cover, climate and land use changes is an urgent challenge for hydrologic science.

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In this work, we used the Regional Hydro-Ecological Simulation System (RHESSys) model (Band *et al*., 1993, 1996; Tague and Band, 2001, 2004) to examine how vegetation change in a mountain environment impacts runoff. RHESSys model simulations were intended to address the dependence of the distribution of land cover types on topography and climate and to examine differences in runoff generated from different vegetation types. The model was also intended to assess interactions between runoff and climate represented by precipitation, air temperature and plant water use in different vegetation types to assess how these interactions may vary at seasonal time steps. The watershed selected for this paper is located at the headwater of the Weber River, Utah (USA). The Weber River is an essential water resource to the state of Utah because its water is used for municipal, irrigation, industrial, power generation and wildlife purposes.

Our runoff sensitivity results suggest that reducing leaf area index (LAI), which tends to decrease transpiration rates, increases wintertime snow accumulation and hence increases runoff during the spring melt season. The model results suggest that annual runoff yield after removing deciduous vegetation is on average about 7% higher than with deciduous vegetation cover, while annual runoff yield after removing coniferous vegetation is on average about 2% higher than that produced with coniferous vegetation cover. These simulations thus help quantify the sensitivity of water yield to vegetation change.

We also found that coniferous and deciduous vegetation at our study watershed (Upper Weber basin, HUC 16020101 in Utah, USA) behave similarly in terms of having evapotranspiration rates limited by available energy only with no limitation due to water availability. This is unusual in semiarid Utah, but it is due to the elevation and precipitation. We think that the results presented in this work should be interpreted as best estimates that serve as hypotheses for how actual ecosystems will respond based on the knowledge and understanding that is embodied in the model. Given that a model is an idealized approximation of realty, there is a need for monitoring programs to verify model predictions.

In what follows, we first review literature on runoff sensitivity to vegetation and land use changes as well as vegetation responses to climate in mountain environments. We then describe our study site and input data. We then proceed with model description, analysis and calibration, followed by results and discussion.

## BACKGROUND

The effect of land use changes on a watershed's hydrological response has been examined by applying physically based and spatially distributed ecosystem, land surface and hydrological models (Abbott *et al*., 1986; Refsgaard, 1987; Bathurst and O'Connell, 1992; Matheussen *et al*., 2000; VanShaar *et al*., 2002; Calder *et al*., 2003; Bathurst *et al*., 2004; Tague *et al*., 2004; Hamlet *et al*., 2007; Christensen *et al*., 2008). It is worth noting here that a physically based model always implies a numerical discretization in one or more space coordinates. Therefore, by physically based model, we mean a description that is based on a scientific physical understanding of the processes involved at a scale consistent with the adopted level of numerical discretization (Jensen and Mantoglou, 1992). In this section, different studies that examined runoff sensitivities to land cover and climate changes are discussed.

The RHESSys framework (Band *et al*., 1993, 1996; Tague and Band, 2001, 2004) has been used in multiple studies to assess the impact of climate and land use change on hydrology. RHESSys provides a detailed representation of snow, runoff, soil and vegetation processes important for addressing our questions. The RHESSys model uses a hierarchical spatial framework that allows different processes to be modelled at their most representative scale. RHESSys uses the Mountain Microclimate Simulator (MTN-CLIM) model (Running *et al*., 1987) to obtain spatially variable climate inputs in mountainous regions. This is important in mountain study areas. RHESSys's flexibility in its modelling element size (tessellation) and representation of vegetation processes are also attractive. RHESSys routes water using an explicit routing model adapted from the Distributed Hydrology Soil Vegetation Model (DHSVM) model (Wigmosta *et al*., 1994; Wigmosta and Lettenmaier, 1999) and includes an evapotranspiration calculation procedure that has a higher sensitivity to LAI (Tague and Band, 2004).

Christensen *et al*. (2008) used RHESSys to assess the sensitivity of transpiration rates to elevation across the Upper Merced River watershed, Yosemite Valley, California, USA. Their model results suggest that elevational differences in vegetation water use and sensitivity to climate were significant. Those elevational transpiration sensitivities to climate were noted as follows: (1) low elevations (1200–1800 m ) showed little interannual variation in transpiration due to topographically controlled high soil moisture, and (2) both middle and high elevations (1800–2600 m ) showed high correlation between precipitation and transpiration. The sensitivity results of Christensen *et al*. addressed the relationships between climate, topography and vegetation water use within the Sierra Nevada ecosystems.

VanShaar *et al*. (2002) selected four catchments within the USA portion of the Columbia River Basin (ranging from 27 to 1033 $km^2$) to simulate the hydrological effects of changes in land cover using the DHSVM (Wigmosta *et al*., 1994; Wigmosta and Lettenmaier, 1999) and the Variable Infiltration Capacity model (VIC) (Liang *et al*., 1994). VanShaar *et al.* (2002) showed that lower leaf area, i.e. decreased vegetation extent, has led to increased snow accumulation, increased streamflow and reduced evapotranspiration. They also mentioned that streamflow changes are greatest during spring snowmelt runoff and evaporation changes are greatest when soils are moister (i.e. spring and early summer). The comparison of VanShaar *et al.* (2002) of the results between the topographically explicit DHSVM and the macroscale VIC models revealed that the trend in snow water equivalent, stream flow and evapotranspiration changes is similar for both models. They discussed how DHSVM is more sensitive than VIC to predict runoff when land cover changes. They attributed that difference of runoff prediction between the two models to longer periods of soil moisture stress in VIC than in DHSVM and to differences in the parameters used in the evapotranspiration formulations. They further suggested that more explicit representation of saturation excess in DHSVM, differences in the calculation of net radiation and VIC's use of architectural resistance, i.e. the aerodynamic resistance between the leaves and the canopy top, used to account for an imperfectly ventilated canopy in the evapotranspiration calculations (Ducoudré *et al.*, 1993), have led to the higher DHSVM sensitivity of runoff to LAI changes.

Hamlet *et al.* (2007) evaluated long-term trends of evapotranspiration, runoff and soil moisture over the western USA for the period 1916–2003 using VIC (Liang *et al.*, 1994). The result of Hamlet *et al.* (2007) show that trends in evapotranspiration in spring and summer are determined primarily by trends in precipitation and snowmelt that determine water availability. They further added that trends in the seasonal timing of evapotranspiration are modest, but during the period 1947–2003 when temperature trends are large, they reflect a shift of evapotranspiration from midsummer to early summer and late spring. Regarding trends in the annual runoff ratio, the authors mentioned that the trends are determined primarily by trends in cool season precipitation, rather than changes in the timing of runoff or evapotranspiration. Hamlet *et al.* (2007) found that the signature of temperature-related trends in runoff and soil moisture is strongly keyed to mean midwinter (December to February) temperatures and that areas with warmer winter temperatures show increasing trends in the runoff fraction as early as February and colder areas as late as June. Hamlet *et al.* (2007) further added that increasing trends in soil moisture on 1 April are evident over much of the western USA.

Different studies assessed climate change impacts on vegetation response within mountain environments (Ryan, 1991; Law *et al.*, 2000; Royce and Barbour, 2001; Boisvenue and Running, 2006; Soulé and Knapp, 2006; Atkin *et al.*, 2008). Model simulations were performed and observations collected in these studies with the intent to a better understanding of the coupling between vegetation and hydrology.

In summary, examining the sensitivity of vegetation water use to topography, climate and watershed management has been studied by applying multiple physically based and spatially distributed ecosystem models. The overarching question that stimulated many of these studies was better understanding of the indirect and interacting hydrologic responses to watershed changes.

## METHODS

### *Study site*

The Weber River near Oakley watershed upstream of USGS gauge # 10128500 has been selected to be the study watershed for this paper. The location of this streamflow gauge within Summit County, UT, is 40°44′14″N and 111°14′50″W referenced from the North American datum of 1927 within the Uinta mountains. The watershed drainage area at this gauge is about 422 $km^2$ (Figure 1). The Weber River near Oakley watershed, located within the Upper Weber basin (HUC 16020101), is the headwater of the Weber River. This selected watershed is a useful study area for examining watershed responses to land cover changes because it has a relatively small contributing area (~420 $km^2$) that makes it responsive to changes in energy. Vegetation within the study watershed is primarily coniferous forest. The streamflow record at this gauge is available since October 1904. Streamflow data were retrieved from the USGS portal http://waterdata.usgs.gov/usa/nwis/uv?

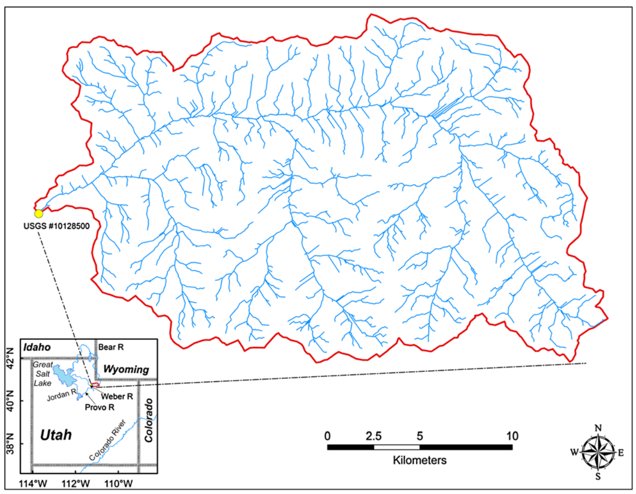


Figure 1. Weber River near Oakley watershed (USGS # 10128500) is located in north eastern Utah within the Uinta Mountains (left lower). The watershed drainage area is about 422 $km^2$

site_no=10128500 accessed on 8 October 2010. Mean annual runoff, $Q$, measured at the outlet of the study watershed is about 443 mm.

*Spatial data*

A digital elevation model with 30 m grid resolution for the study watershed was obtained from the National Elevation Dataset (http://seamless.usgs.gov/website/seamless/viewer.htm) and was used to derive the slope and aspect grids for the model inputs. The elevation of the study watershed ranges from 2000 to 3640 m (Figure 2) with mean elevation of 2758 m.

The watershed soil's texture map was obtained from the Soil Survey Geographic dataset through the Geospatial Data Gateway (http://datagateway.nrcs.usda.gov/). The watershed soil texture is mainly loam with small areas of clay loam. The mean soil depth is about 2.8 m.

Vegetation and land use information was obtained from the National Land Cover Dataset (http://gisdata.usgs.net/website/MRLC/viewer.php). We grouped vegetation and land use into eight categories: coniferous forest, deciduous forest, shrub, mixed forest, grass, no vegetation, agriculture and urban. The dominant types of vegetation within this watershed are coniferous forests (~49%), shrub (~21%) and deciduous forests (~17%) (Figure 2). The watershed is mostly undeveloped lands, i.e. forest, with few agricultural lands that are close to small urban areas within valleys close to the watershed outlet.

*Climate data*

Long-term climate data in the form of daily precipitation ($P$), minimum and maximum air temperature ($T$) and wind speed ($w$) were obtained from the Surface Water Modeling group at the University of Washington (http://www.hydro.washington.edu/Lettenmaier/Data/gridded/index_hamlet.html). The development of this gridded dataset was described by Hamlet and Lettenmaier (2005). This dataset includes daily 1/8th-degree resolution gridded meteorological data for 1 January 1915 to 31 December 2003. We extracted the data for our study watershed from the Great Basin region group in this dataset (Figure 3). There is no wind speed data prior to 1949, so long-term averages are used. July is the hottest month during the year at this watershed with maximum daily air temperature that varies between 17 and 30 °C.

Mean annual precipitation on the study watershed is about 830 mm. We summarize the precipitation, runoff and evapotranspiration $\left(\overline{E}\right)$ annual information for the study watershed during 1921–2003 water years in Table I. The annual average actual evapotranspiration was calculated using mass balance $\left(\overline{E} = \overline{P} - \overline{Q}\right)$, while potential evapotranspiration $\left(\overline{E}_p\right)$ was obtained from Vörösmarty *et al.*(1998).

Budyko (1974) uses $\left(\overline{E}_p/\overline{P}\right)$ as a dryness index to classify the hydroclimate. He suggests that when $\overline{P}$ is large relative to $\overline{E}_p$ for a watershed, water is in abundant supply and evapotranspiration from this watershed is limited only by energy. When precipitation is short relative to $\overline{E}_p$ ($\overline{E}_p/\overline{P}$ is large), the evapotranspiration from this watershed is limited only by water availability. Budyko (1974) developed an empirical function $\overline{E}/\overline{P} = \varphi\left(\overline{E}_p/\overline{P}\right)$ that partitions $P$ into $E$ and $Q$. For our study watershed, $\overline{E}_p/\overline{P} = 0.7$ and $\overline{Q}/\overline{P} = 0.53$. These indicate that this is an energy-limited watershed, something unusual for Utah, which is perceived to be generally semi-arid. This is due to the high elevation of this watershed that receives considerable snow and where $\overline{E}_p$ is small reduced due to low air temperatures at the elevation of the study site.

*Model description*

The RHESSys model described by Band *et al.* (1993, 1996) and Tague and Band (2001, 2004) is a Geographic Information System (GIS) based, hydro-ecological modelling framework designed to simulate carbon, water and nutrient fluxes. As a hydrologic model, RHESSys is intermediate in terms of its complexity as compared with more complex process-based hydrologic models such as

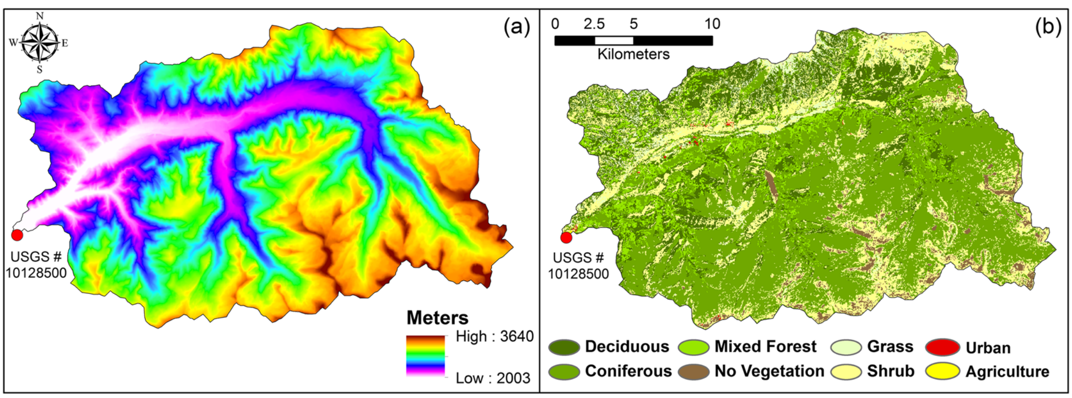


Figure 2. Spatial input data: (a) digital elevation model (30-m grid size) and (b) land cover. Land cover from the National Land Cover Dataset 1992

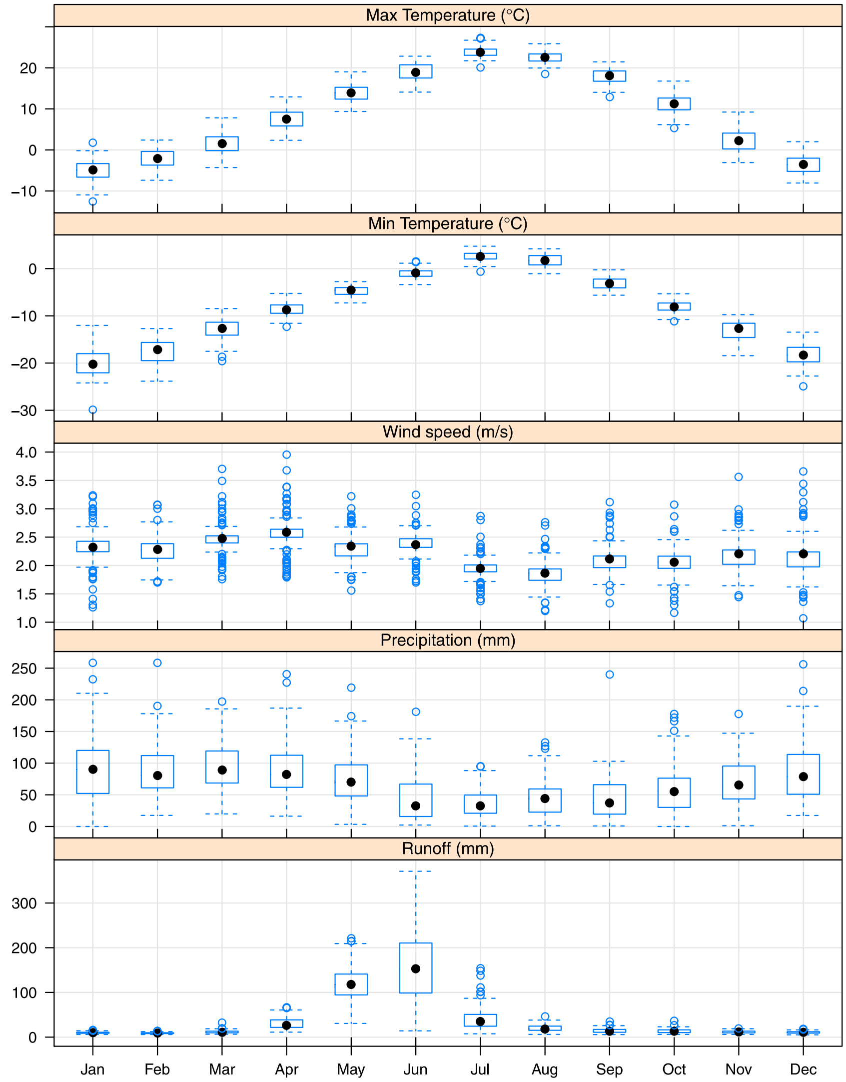


Figure 3. Input data over the study watershed and measured at the watershed outlet during 1915–2003. Boxplots of average monthly values of maximum, minimum air temperature and wind speed, and monthly precipitation and runoff amounts. Precipitation and runoff amounts were summed monthly. Climate data from Hamlet and Lettenmaier (2005) and runoff measured at USGS gauge # 10128500

Table I. Weber River near Oakley, UT (USGS # 10128500), annual water balance estimates (1921–2003)

| *P* (mm) | | | | *Q* (mm) | | | | *E* (mm) | |
|---|---|---|---|---|---|---|---|---|---|
| Min | Mean | Median | Max | Min | Mean | Median | Max | Actual | Potential |
| 438 | 829 | 821 | 1250 | 164 | 443 | 447 | 794 | 386 | 555 |

Runoff (*Q*) from the USGS national water information system (http://waterdata.usgs.gov/nwis), precipitation (*P*) from Hamlet and Lettenmaier (2005), mean annual evapotranspiration (*E*) estimated from both mass balance and potential evapotranspiration obtained from Vörösmarty *et al.* (1998).

MIKE-SHE (MIKE SHE is an integrated catchment modeling system emerged from the Systéme Hydrologique Européen (SHE) model and developed by DHI Water & Environment) (Refsgaard and Storm, 1995). RHESSys combines both a set of physically based process models and a methodology for partitioning and parameterizing the landscape over spatially variable terrain ranging from ten metres to hundreds of kilometres. The version of RHESSys used for this work (5.14.4) includes both surface and subsurface storage routing and a deep groundwater store (Tague *et al.*, 2008). The RHESSys model is able to simulate interactions between carbon, water and nutrient fluxes and climate patterns within a mountainous environment. Water is explicitly routed between spatial patches, representing spatial heterogeneity in soil moisture and lateral water flux to the stream. The RHESSys hydrologic process models have been adapted from several pre-existing models, and they include the following: snow accumulation and melt, interception, infiltration, transpiration, soil and litter interception, evaporation and shallow and deep groundwater subsurface lateral flow. RHESSys uses a hierarchical spatial framework that allows different processes to be modelled at their most representative scale. Specific algorithms within these original models have been modified to reflect various developments in the associated literature or to fit within the RHESSys modelling framework. Most processes are run at a daily time step. RHESSys uses the Penman Monteith (Monteith, 1965) method for evaporation and sublimation of intercepted water, transpiration and soil and litter evaporation processes. RHESSys uses the Jarvis model for stomatal conductance calculations based on air temperature, vapour pressure deficit, wind speed and other environmental factors (such as light and $CO_2$) (Jarvis, 1976). The full details of all process modules in RHESSys are documented by Tague and Band (2004).

RHESSys partitions the landscape into distributed elements hierarchically organized into *basin* (watershed), *zone*, *hillslope*, *patch* and *stratum*. In this work, *zones* representing climate information have been partitioned following the 1/8th-degree climate grid from Hamlet and Lettenmaier (2005). There are eight different zones spanning our study watershed (Figure 4). *Hillslopes* were generated using the watershed analysis routine (*r.watershed*) in Geographic Resources Analysis Support System (GRASS Development Core Team, 2010) with contributing area threshold of 0.16 $km^2$ resulting in 2318 hillslopes (Figure 4). We obtained the stream network contributing area threshold objectively from a stream drop test following theory described in Tarboton *et al.* (1991, 1992). Each hillslope was treated as a single model element (i.e. *patch*). *Stratum* is used for canopy information and inherits the *patch* spatial setting (i.e. *hillslope* in this work).

Daily climate data of minimum and maximum air temperature as well as precipitation drive RHESSys flux estimates. Meteorological variables including radiation, partitioning of rain and snow, saturation vapour pressure and relative humidity are simulated using MTN-CLIM model (Running *et al.*, 1987). MTN-CLIM extrapolates meteorological variables from the point of measurements (*zones*) to the modelling unit of interest (*hillslope*) making corrections for differences in elevation, slope and aspect between the point of measurements and targets (*hillslopes*). Lapse rates used in this work to adjust air temperatures and dewpoint spatially are 0.0053 and 0.0015 °C/m, respectively (Christensen *et al.*, 2008).

Canopy heights and species specific vegetation parameters (Myers and Edminster, 1972; Kaufmann and Troendle, 1981; Ryan, 1990; White *et al.*, 2000; Rueth and Baron, 2002) are available as standard RHESSys libraries. The six vegetation categories grouped for the study watershed were linked with vegetation parameters from RHESSys libraries.

Initial LAI values at the *hillslope* level for our study watershed were found by first setting LAI as zero over the whole study watershed. We then ran RHESSys model letting vegetation to grow for couple hundred years. This has been carried out by spinning the model, for the time span available from input data, multiple times letting the model to output the *hillslopes* stores and LAI at the end of each spin.

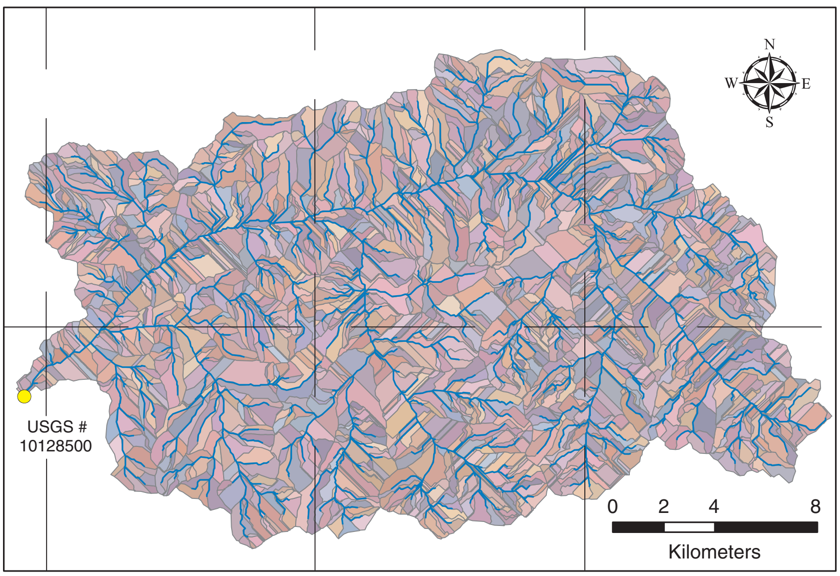


Figure 4. Hillslopes for the Weber River near Oakley watershed used as modelling units (2318 patches) in RHESSys framework. Eight zones, displayed as rectangles with dotted lines, were used for climate processing from eight grids (Hamlet and Lettenmaier, 2005)

 

During the spinning of the model, canopy state variables that include but not limited to specific leaf area, leaf to stem ratio and steam to coarse root ratio were updated. This spinning process was repeated until the RHESSys model produced LAI value (simulated aggregated LAI was about 4.0) close to LAI information obtained from the Vegetation/Ecosystem Modeling and Analysis Project (VEMAP, http://www.cgd.ucar.edu/vemap/v2results.html) phase 2 experiments dataset (aggregated LAI is about 4.0). VEMAP is a collaborative program led by the National Center for Atmospheric Research to simulate and understand ecosystem dynamics for the continental USA (Kittel *et al.*, 2004). VEMAP dataset includes climate, soil and vegetation data on a 0.5-degree resolution grid.

For this work, we used an explicit routing model approach adapted from DHSVM (Wigmosta *et al.*, 1994) to route the water horizontally. The explicit routing model approach models saturated subsurface interflow and overland flow via explicit connectivity. An important modification from the grid-based routing in DHSVM is the ability to route water between arbitrarily shaped surface elements. This allows greater flexibility in defining surface patches and varying shape and density of surface tessellation.

### *Model parameters and calibration*

It is well known that properties of natural earth materials are highly variable in space. This brings to our attention that one of the problems in distributed hydrological models is that they attempt to provide a deterministic description of flow processes. Theoretically, these problems, i.e. heterogeneity problems, have been argued that they can be addressed by allowing parameter values to accommodate the physical characteristics of the flow processes when different parameters vary from grid element to grid element according to measurements (Abbott *et al.*, 1986; Bathurst, 1986). Moreover, meteorological variables tend to have a large temporal and spatial variation. These parameter requirements imply in practice impossible field measurements that are required to fulfil all grid elements in a deterministic model application over a certain scale. Hence, considerable limitations to distributed hydrological models arise when we interpret their results. It is important to draw the reader attention to Beven's (2001) discussion on rainfall runoff models parameter estimation and predictive uncertainty. Beven summarizes the key points on rainfall runoff models parameter estimation and predictive uncertainty as follows: (1) it is most unlikely that there will be one right answer, (2) calibrated parameter values may only be valid inside the particular model structure used, (3) the model results will be much more sensitive to changes in the values of some parameters than to changes in others and (4) different performance measures will usually give different results in terms of both the 'optimum' values of parameters and the relative sensitivity of different parameters. Beven (2001) has also summarized different methods of model calibration that are available. He classified these model calibration methods into three classes. The first model calibration methods class assumes an optimum parameter set and ignores the estimation of predictive uncertainty around that optimum parameter set (Sorooshian and Gupta, 1995). The second model calibration methods class assumes an optimum parameter set and estimate predictive uncertainty around that optimum parameter set (Melching, 1995), while the third model calibration methods class rejects the idea that there is an optimum parameter set in favour of the idea of *equifinality* of models (Gupta *et al.*, 1998; Yapo *et al.*, 1998). Equifinality is a concept that there may be many models of a catchment that are acceptably consistent with the observation available.

Mathematical representations of the key controls on ecosystem processes are embedded in RHESSys in the form of models. RHESSys uses many parameters to describe typical soil, vegetation and land use characteristics. Literature-based estimates have been used to compile parameters for common vegetation and soil types. A substantial effort has been made to reduce the number of calibrated parameters within RHESSys to four hydrologic parameters, which are the following: (1) the decay of hydraulic conductivity with depth ($m$), (2) saturated soil hydraulic conductivity at the surface ($k$), (3) the fraction of recharge that bypasses the shallow subsurface flow system to deeper groundwater storage ($gw1$) and (4) the drainage rate of deeper groundwater store ($gw2$). In this work, the model was calibrated to daily streamflows at the watershed outlet during the 1994 water year. The 1994 water year is relatively a dry year with annual precipitation of 638 mm. Monte Carlo simulation was used to generate 5000 sample parameter sets from independent uniform distributions over the feasible parameter ranges determined from the literature ranges for $m$, $k$, $gw1$ and $gw2$ parameters. Each was used as input to the model, and model performance was assessed using the Nash–Sutcliffe metric on daily flows, Nash–Sutcliffe metric on log daily flows and total annual flow error (Figure 5). From these simulations, we selected a group of behavioural parameter sets based on percent error (*Qerr*) between daily simulated and observed runoff and Nash–Sutcliffe (*NS*) performance metric for daily simulated and observed runoff (also used with log flows, *NSlog*). We note that model results are more sensitive to changes in values of $gw1$ and $gw2$ parameters than to changes in the other parameters (Figure 5). We used 1921–2003 water years' runoff record for model verification.

 

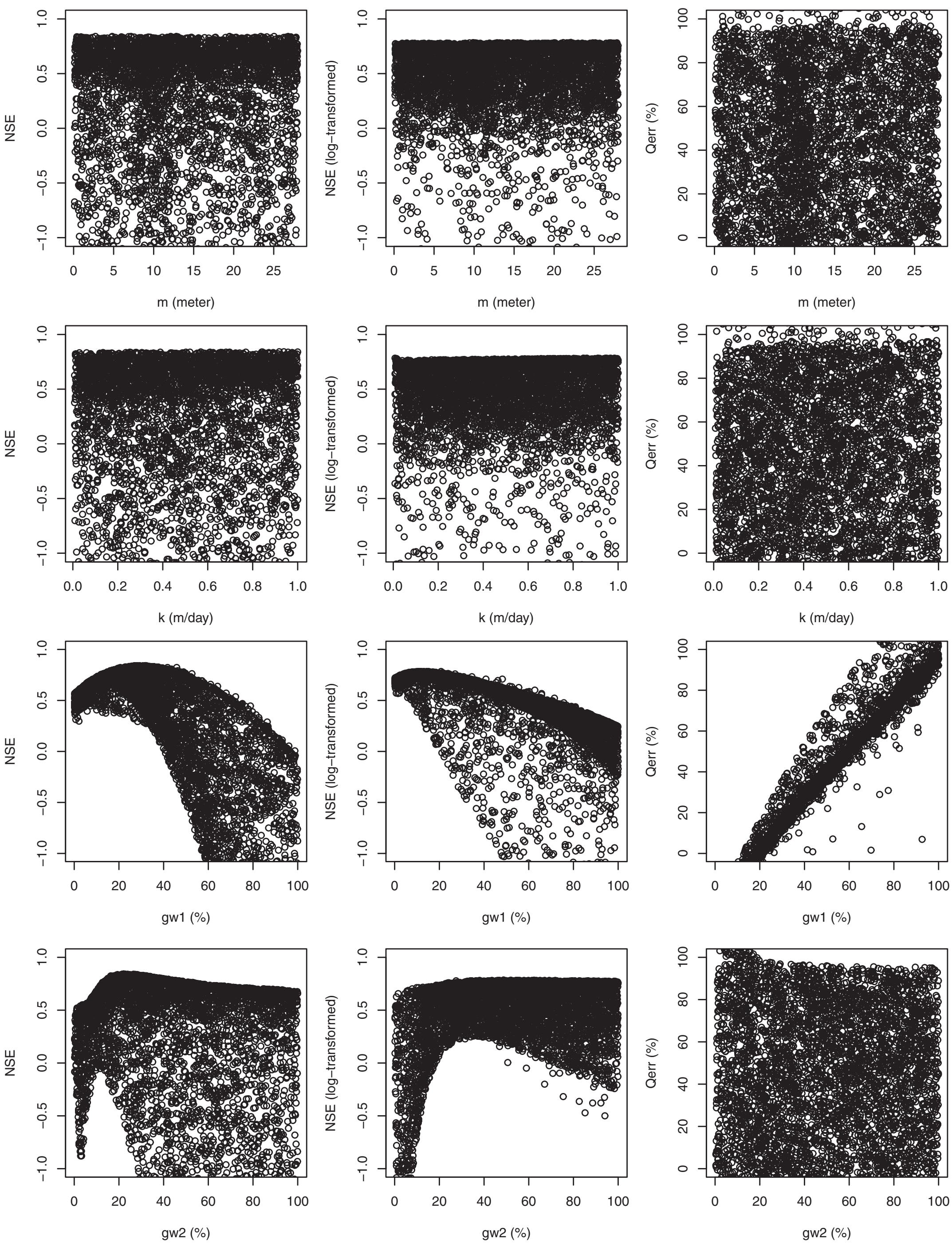


Figure 5. Five thousand Monte Carlo simulation sample parameter sets over the literature parameter ranges for RHESSys calibration parameters (*m*, *k*, *gw*1 and *gw*2). Nash–Sutcliffe efficiency metric on daily flows (*NSE*), Nash–Sutcliffe efficiency metric on log daily flows (*NSE log-transformed*) and annual flow error (*Qerr*) metrics were used to pick a reasonable set of RHESSys calibration parameters. The 1994 water year observed runoff record was used for calibration

## EXPERIMENT

The experiment we conducted for this paper comprised two independent parts with the goal of examining the sensitivity of runoff to land cover changes. The first part of the experiment was selection of a hillslope within our study watersheds that is dominated with coniferous cover (area 0.222 $km^2$, mean elevation 2621 m and mean slope 28°) and conducted multiple simulations with different vegetation covers (see hillslope labelled (1) in Figure 6). Multiple vegetation covers that include conversion to grass, deciduous cover and no vegetation cover scenarios

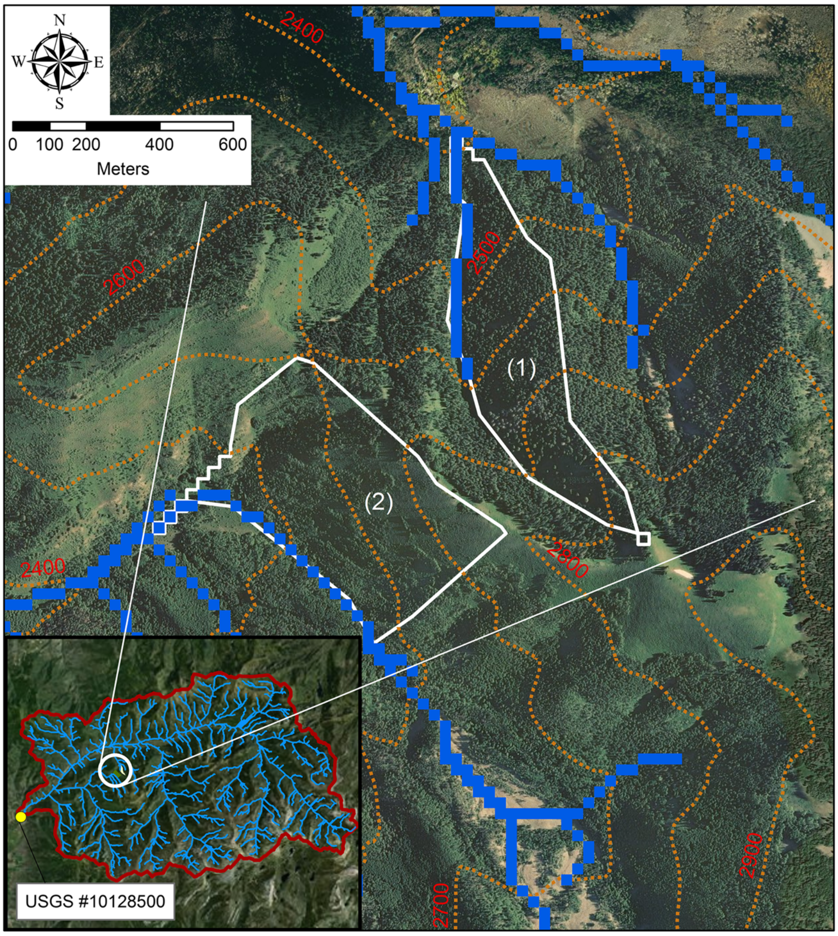


Figure 6. Two hillslopes, coniferous labelled with (1) and deciduous labelled with (2), used for examining the sensitivity of runoff to land cover change. The background image is ESRI base map with resolution of 15 cm. Dotted lines are elevation contours with 100 m intervals. The two hillslopes location within the study watershed (USGS # 10128500) is shown in the lower left (insert)

were evaluated. Comparison between runoff generated under each vegetation cover was carried out. Analysis of relative evapotranspiration coefficients, runoff ratio ($Q/P$) sensitivity to vegetation change and runoff prediction models has been evaluated. By relative evapotranspiration coefficient, we mean the ratio of actual evapotranspiration to potential evapotranspiration. Actual evapotranspiration is the rate of evapotranspiration from a surface or vegetation canopy to the atmosphere under the prevailing meteorological conditions and water availability. Potential evapotranspiration is the rate of evapotranspiration from a surface or vegetation canopy with no limitation due to water availability.

The second part of this work experiment was similar to the first part but differs in the selection of a hillslope. The hillslope selected in the second part is dominated with deciduous vegetation cover (area 0.314 $km^2$, mean elevation 2600 m and mean slope 25°) (see hillslope labelled (2) in Figure 6). This means that the last vegetation change scenario examined for runoff sensitivity to vegetation change implies the change from deciduous to coniferous cover. This two-part experiment should be viewed separately with no intent of characterizing coniferous and deciduous trees differences because the hillslopes chosen appear to have different shape and physical characteristics.

## RESULTS

We generated results from each parameter set in the behavioural group and found that patterns and trends of runoff obtained from the different sets were all essentially the same (runoff sensitivity results are presented later in Figure 12). Hence, in what follows (Figures 7–11), we have chosen one parameter set to present the results and illustrate the sensitivities that we are interested in. This parameter set is given in Table II, and results with this parameter set are able to capture about 82% of the variability seen in observed daily runoff during the calibration year. Annual simulated runoff had a 5.97% error when compared with annual runoff observed. Figure 7 gives daily simulated *versus* observed runoff

 

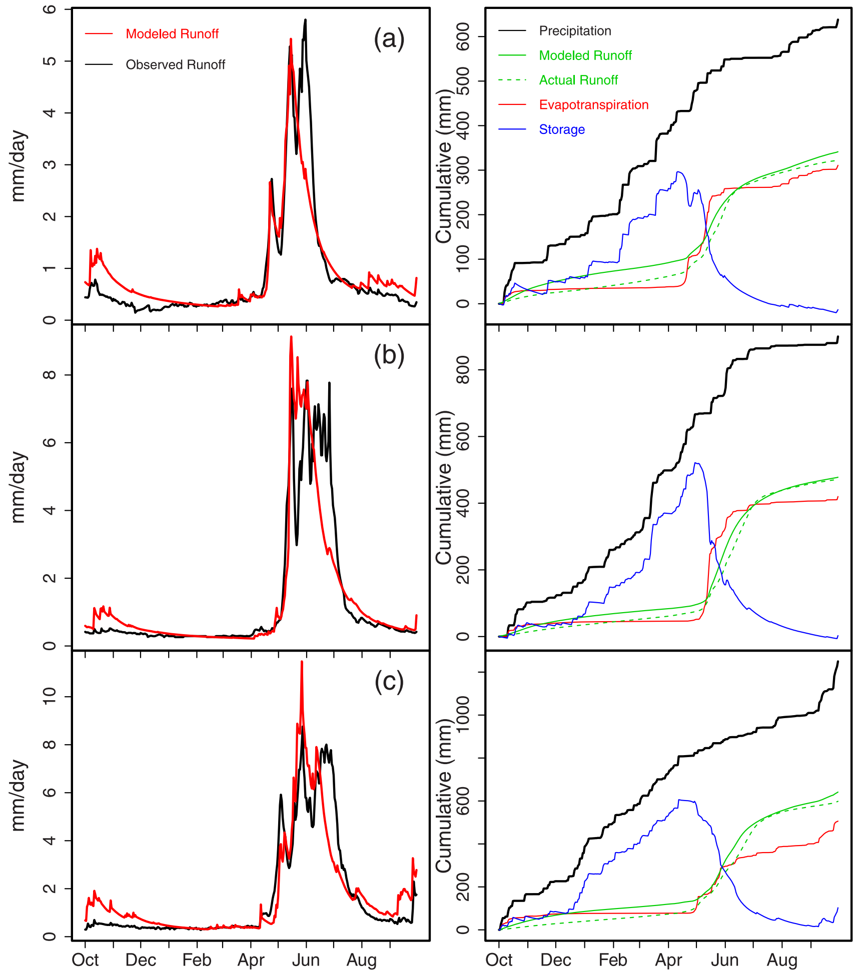


Figure 7. Daily simulated *versus* observed runoff (mm) for the Weber River near Oakley watershed in calibration of RHESSys. Dry [October 1993 to September 1994, row (a)], average [October 1943 to September 1944, row (b)] and wet [October 1981 to September 1982, row (c)] water yield year results are shown. Right panel plots give cumulative runoff (observed and simulated), evapotranspiration and storage simulated with observed precipitation during corresponding year to the left

(mm) for the study watershed during calibration year (panel a), average yield year (panel b) and a wet yield water year (panel c). In Figure 7, we also give cumulative simulated runoff, evapotranspiration and storage (offset to be 0 at the start) as well as observed precipitation and runoff. Nash–Sutcliffe efficiency for daily and log-transformed daily runoff was 0.82 and 0.73, respectively (panel a). Average water year (panel b) Nash–Sutcliffe efficiency for daily and log-transformed daily runoff was 0.78 and 0.87, while wet water year (panel c) efficiencies were 0.78 and 0.76, respectively. The model did a good job in capturing the variability seen in daily runoff during spring but with less degree during summer time. This is shown with the Nash–Sutcliffe efficiency of log-transformed daily runoff value of 0.73 (panel a), 0.87 (panel b) and 0.76 (panel c). We feel that this level of accuracy is acceptable to pursue this modelling exercise given the objectives we had of examining the sensitivity of runoff to land cover change.

Figure 8 gives monthly observed and simulated runoff for the study watershed in verification of RHESSys model during 1921–2003 years . In general, the model did well at capturing timing of onset and end of seasonal runoff but was slightly off in some estimates of peak flows. The model was able to capture on average about 70% of the variability seen in daily runoff, 75% of the variability in daily log-transformed flows and had about 2.83% error in estimating total annual flows during 83 years. These simulation efficiencies have to be considered in examining the results of this work. The uncertainty and limitations seen are due to the nature of modelling that could be related to error in inputs, parameters and process representation. Calibration parameters with performance metric for both calibration and verification periods were summarized in Table II.

Because we were interested in examining the sensitivity of runoff to land cover changes, examination of water use from different vegetation covers is an important

 

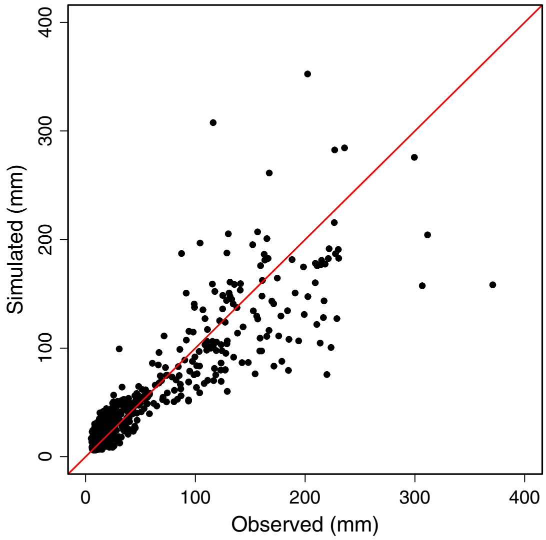


Figure 8. Scatterplot of monthly observed and simulated runoff in millimetres for the Weber River near Oakley watershed in verification of RHESSys during 1921–2003

component. We analysed 83 years of RHESSys simulations from the two selected hillslopes that had different vegetation covers that include runoff, storages and evapotranspiration estimates at each hillslope. We found that the relative evapotranspiration coefficient, $\overline{r}_{lc}$ ; $\overline{r}_{lc} = \overline{E}/\overline{PET}$, in deciduous and coniferous trees at this watershed is quite similar (Table III). Our results suggest that the mean annual relative potential evapotranspiration coefficient for deciduous trees is about 0.922 and for coniferous trees is about 0.964. This suggests that coniferous and deciduous vegetation at our study watershed behaves similarly in terms of having evapotranspiration rates limited to available energy only with no limitation due to water availability. This also suggests that the model predictions align with our mass balance observations stated earlier (i.e. energy-limited watershed). The RHESSys model predicts that mean annual actual evapotranspiration from coniferous trees is about 351 mm, while the mean annual actual evapotranspira-

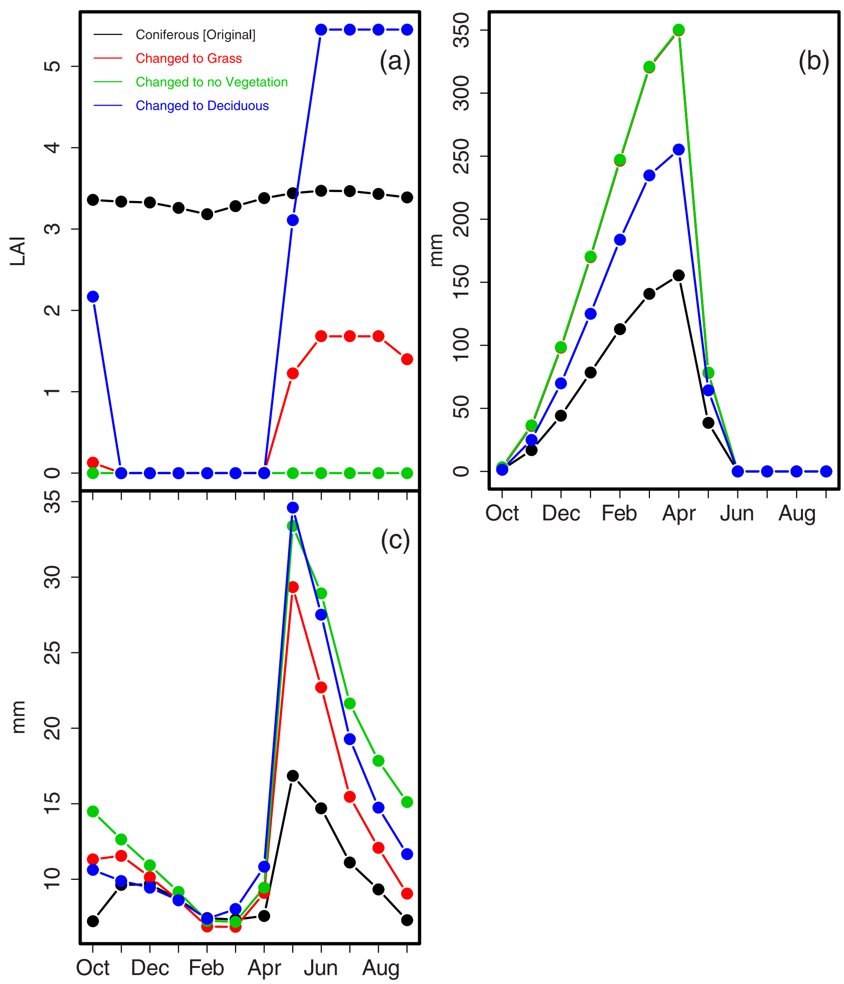


Figure 9. Leaf area index (LAI), snow water equivalent and runoff seasonal sensitivities to vegetation change at coniferous hillslope. (a) Monthly average LAI, (b) monthly average snow water equivalent and (c) monthly average runoff; 83 years simulation result. Vegetation change scenarios include conversion from coniferous to grass (red), no vegetation (green) and deciduous (blue)

 

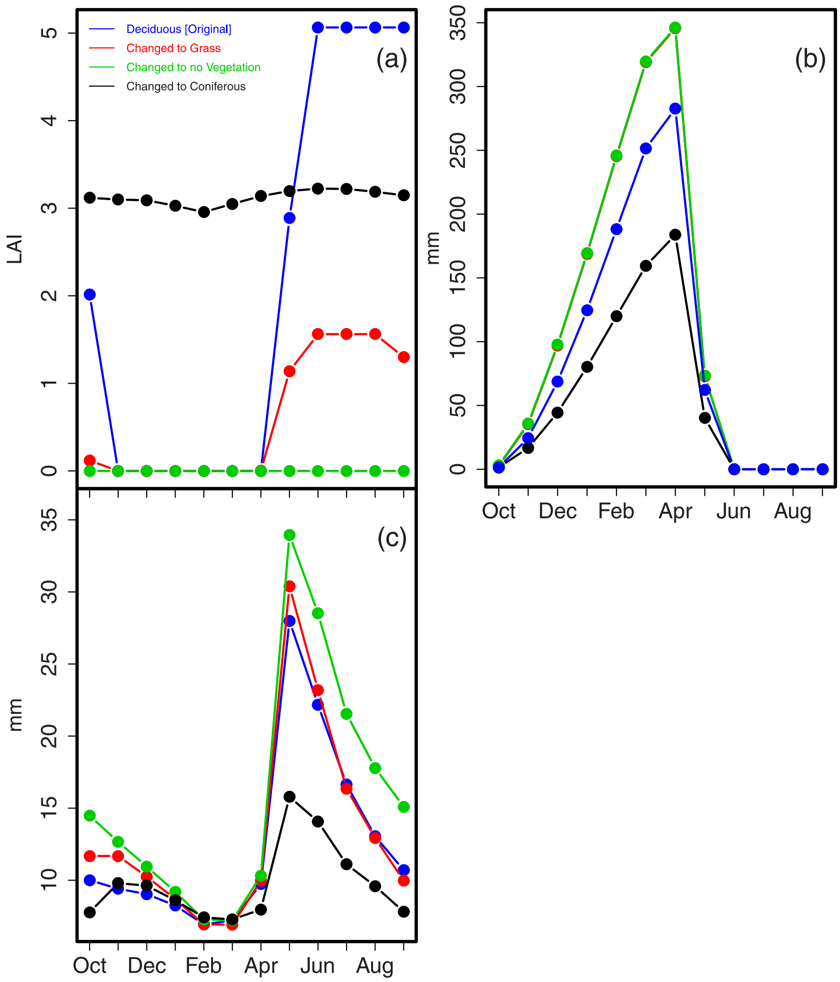


Figure 10. Leaf area index (LAI), snow water equivalent and runoff seasonal sensitivities to vegetation change at deciduous hillslope. (a) Monthly average LAI, (b) monthly average snow water equivalent and (c) monthly average runoff; 83 years simulation result. Vegetation change scenarios include conversion from deciduous to grass (red), no vegetation (green) and coniferous (black)

tion from deciduous trees is about 354 mm. Precipitation on both selected hillslopes is the same. The RHESSys calculations of potential evapotranspiration (PET) in Table III are less than those of PET from Vörösmarty *et al*. (1998). These differences may be due to differences in leaf conductance and canopy resistance or climate data resolution and do not affect our findings because it is the relative differences between vegetation that we are interested in more than absolute values. In Table III, we give a summary of model evapotranspiration prediction information from the two study hillslopes with deciduous and coniferous vegetation covers as well as estimates of the relative evapotranspiration coefficients. Annual minimum and maximum, mean and standard deviation information for deciduous and coniferous vegetation covers is presented (Table III).

The specific question of this paper is how vegetation changes in a mountain environment impact runoff. Figures 9 and 10 give sensitivity of runoff to vegetation results from the two-part experiment explained earlier. Mean monthly averages for 83 years were evaluated to produce both figures. We give seasonal average LAI (panel a), seasonal average snow water equivalent (panel b) and seasonal average runoff (panel c) sensitivities to vegetation change on the coniferous hillslope in Figure 9 (experiment part 1). This is repeated for the deciduous hillslope in Figure 10 (experiment part 2).

RHESSys modelled LAI as expected in that no vegetation cover had zero LAI while deciduous cover had higher LAI during the late spring–summer seasons. RHESSys predicts increased snow water equivalent in areas of decreased LAI as a result of no canopy and litter interception for non-vegetated areas. Panel b, which gives snow water equivalent predictions, indicates higher snow amounts in non-vegetated and grass covers and lower snow amounts for coniferous and deciduous covers. As a result of these differences

 

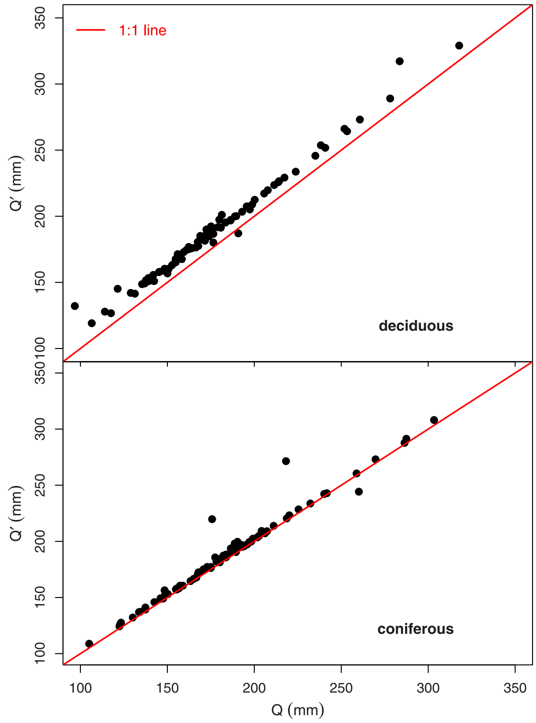


Figure 11. Annual runoffs with vegetation cover being converted from deciduous/coniferous cover to no vegetation cover

in snow accumulated during winter and evapotranspiration during late spring and summer seasons, RHESSys predicts noticeable changes in runoff for the different vegetation changes scenarios (Figure 9). Let us look at the case where we converted coniferous cover to no vegetation cover (green line in Figure 9). We realize that this vegetation cover change scenario has indicated a higher runoff with respect to other vegetation cover change scenarios tested. Our interpretation is that changes in vegetation cover have affected the water balance in two ways. First, reduced LAI results in lower annual evapotranspiration. This tends to increase runoff relative to evapotranspiration. Second, during winter, reduced LAI decreases canopy interception that leads to increased wintertime snow accumulations and hence snow available for runoff during the early spring melt season. Increased LAI during spring melt season tends to delay the snow melting process as a result of reduced radiation under high LAI surfaces relative to low LAI surfaces.

In Figure 10, we see that higher runoff amounts were obtained when we changed the deciduous cover to anything else because deciduous cover had the highest LAI than other land cover change scenario tested (going from high LAI to low LAI). Figure 10 or experiment part 2 helped us to reach the runoff sensitivities to vegetation changes at deciduous hillslope covers. The information obtained from both Figures 9 and 10 was aggregated to annual average, which is shown in Figure 11.

In Figure 11, we give runoff information from the two selected hillslopes that had deciduous and coniferous vegetation covers with existing and removing vegetation conditions. The $x$-axis gives the existing vegetation yield ($Q$), while the $y$-axis gives yield after removing vegetation cover ($Q'$). Model simulations suggest that annual runoff after removing vegetation can be approximated as follows:

$$\begin{aligned} Q'_{deciduous} &= 1.067\ Q_{deciduous} \\ Q'_{coniferous} &= 1.021\ Q_{coniferous} \end{aligned} \tag{1}$$

Both these relations have $R^2$ value of about 0.98 (Figure 11). However, attention should be paid to the

Table II. Selected RHESSys calibration parameters used to drive model simulations

| Period | $m$ (m) | $k$ (m/day) | $gw1$ (%) | $gw2$ (%) | $NS$ | $NSlog$ | $Qerr$ (%) |
|---|---|---|---|---|---|---|---|
| Calibration | 9.75 | 0.40 | 23.10 | 30.40 | 0.82 | 0.73 | 5.97 |
| Verification | | | | | 0.70 | 0.75 | 2.83 |

Nash–Sutcliffe ($NS$) performance metric for daily simulated and observed runoff (also used with log flows, $NSlog$) and percent error ($Qerr$) between daily simulated and observed runoff for calibration (1993–1994) and verification (1921–2003) periods were used to select the model solution.

Table III. Annual evapotranspiration information for study hillslopes that have deciduous and coniferous vegetation covers; evapotranspiration and potential evapotranspiration results from RHESSys model simulations

| Vegetation | $\mu_E$ | $\overline{PET}$ | $\min(r_{LC})$ | $\bar{r}_{LC}$ | $\max(r_{LC})$ | $\sigma(r_{LC})$ |
|---|---|---|---|---|---|---|
| Deciduous | 354 | 383 | 0.844 | 0.922 | 0.962 | 0.030 |
| Coniferous | 351 | 364 | 0.881 | 0.964 | 0.997 | 0.028 |

$\mu_E$ is the evapotranspiration arithmetic mean in millimetres; $\overline{PET}$ the potential evapotranspiration arithmetic mean in millimetres; $\bar{r}_{LC}$ the mean relative potential evapotranspiration coefficient, where $r_{LC} = E/PET$; $\min(r_{LC})$ the minimum relative potential evapotranspiration coefficient; $\max(r_{LC})$ the maximum relative potential evapotranspiration coefficient; and $\sigma(r_{LC})$ the relative potential evapotranspiration coefficient unbiased standard deviation.

 

runoff offset in this Figure (i.e. runoff gain due to vegetation loss). Model simulations suggest that runoff offsets when removing coniferous cover are relatively small (Figure 11). We think that these small offsets are mainly due to the small LAI values seen at the coniferous hillslope covered selected. We feel that these runoff prediction models are useful in examining changes in runoff generated from different vegetation types. Table IV gives summary of runoff ratio information produced at the two selected hillslopes under the three conditions examined (existing vegetation cover, conversion to grass cover and conversion to no vegetation cover). The runoff increases in both deciduous and coniferous covers (6.7% in deciduous and 2.1% in coniferous) associated with vegetation removal can be seen in runoff ratio changes (Table IV). Annual minimum, mean, median, maximum, standard deviation and coefficient of variation runoff ratio information is also presented (Table IV).

Sensitivity of our runoff results discussed earlier (Figure 11) to uncertainty in calibrated parameters has been tested. A group of five behavioural parameter sets was selected in terms of the Nash–Sutcliffe metric on daily observed flows, Nash–Sutcliffe metric on log daily observed flows and total annual flow error during the calibration year (Table V). This group of behavioural parameter sets was then used in driving RHESSys model to reach runoff estimates from the two selected hillslopes that had deciduous and coniferous vegetation covers with existing and removing vegetation conditions. Figure 12 shows boxplots of the differences in annual runoff from vegetation changes at different behavioural parameter sets solutions during 83 years period. Outliers have been omitted from Figure 12 to enhance readability.

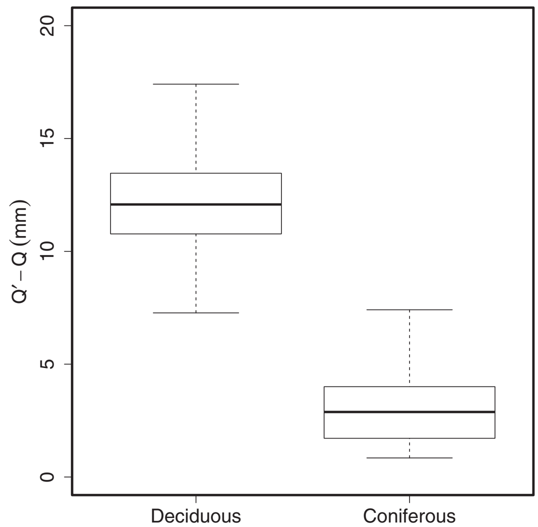


Figure 12. Model prediction sensitivity to five behavioural parameter sets. Differences in annual runoffs from vegetation cover being converted from deciduous/coniferous cover to no vegetation cover. ($Q'$) and ($Q$) symbols are yield after removing vegetation cover and yield with existing vegetation cover, respectively

Table IV. Runoff ratio ($Q/P$) annual sensitivity analysis for study hillslopes to vegetation change; runoff results from RHESSys simulations

| | Deciduous | | | | | | Coniferous | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Min | Mean | Median | Max | sd | CV | Min | Mean | Median | Max | sd | CV |
| Existing condition | 0.189 | 0.243 | 0.240 | 0.366 | 0.036 | 0.146 | 0.197 | 0.254 | 0.253 | 0.352 | 0.036 | 0.140 |
| Conversion to grass | 0.188 | 0.246 | 0.239 | 0.358 | 0.037 | 0.149 | 0.188 | 0.243 | 0.238 | 0.332 | 0.035 | 0.145 |
| Conversion to no vegetation | 0.201 | 0.261 | 0.257 | 0.372 | 0.038 | 0.146 | 0.201 | 0.260 | 0.259 | 0.356 | 0.037 | 0.143 |

Three vegetation change conditions that include existing vegetation, conversion to grass and conversion to no vegetation are shown. sd is standard deviation, and CV is coefficient of variation (CV = sd/mean). Mean annual precipitation on the study hillslopes is 732 mm.

Table V. Selected RHESSys parameter sets used to drive model simulations for sensitivity analysis

| Set | *m* (m) | *k* (m/day) | *gw*1 (%) | *gw*2 (%) | *NS* | *NSlog* | *Qerr* (%) |
|---|---|---|---|---|---|---|---|
| 1 | 11.31 | 0.02 | 27.10 | 33.60 | 0.81 | 0.76 | 6.25 |
| 2 | 18.15 | 0.01 | 24.50 | 23.90 | 0.81 | 0.76 | 1.43 |
| 3 | 3.71 | 0.90 | 22.20 | 33.30 | 0.82 | 0.76 | 4.53 |
| 4 | 1.76 | 0.57 | 18.50 | 30.90 | 0.80 | 0.76 | −0.37 |
| 5 | 15.53 | 0.84 | 19.60 | 28.80 | 0.82 | 0.75 | 1.25 |

Model parameters (*m*, *k*, *gw*1 and *gw*2) and *NS*, *NSlog* and *Qerr* symbols are as in Table II.

 

Figure 12 suggests that the runoff yield confidence limits are in the range of 12 mm with deciduous cover removal and in the range of 3 mm with coniferous cover removal. We deduce then that the RHESSys model used in this work behaves similarly within the range of the behavioural parameters outlined in Table V.

## CONCLUSIONS AND DISCUSSION

This paper examined the sensitivity of runoff to land cover changes. RHESSys simulations from two hillslopes with different vegetation covers were evaluated. Our results suggest that during winter reduced LAI decreases canopy interception that results in increased wintertime snow accumulations and hence snow available for runoff during the early spring melt season. Increased LAI during spring melt season tends to delay the snow melting process as a result of reduced radiation under high LAI surfaces relative to low LAI surfaces. The model results suggest that annual runoff yield after removing deciduous vegetation is on average about 7% higher than with deciduous vegetation cover, while annual runoff yield after removing coniferous vegetation is on average as about 2% higher than that produced with coniferous vegetation cover. The contribution of this work primarily lies on the examination of water use sensitivity to plants functions in a mountain environment using numerical simulations. These simulations thus help quantify the sensitivity of water yield to vegetation change.

In this work, our goal was to answer the specific question of how does vegetation change in mountain environment impact runoff. The approach was to conduct a numerical modelling experiment using the RHESSys model to examine the sensitivity of runoff to vegetation change. Our use of two adjacent hillslopes was not intended to characterize coniferous and deciduous trees differences because the hillslopes chosen appear to have different shape and physical characteristics. Rather, we used these two hillslopes as if we are doing two experiments, experiment number 1, which was carried out for coniferous cover hillslope to examine the runoff sensitivity to changes in vegetation covers holding everything else constant, and experiment number 2, which was carried out for deciduous cover hillslope to examine the runoff sensitivity to changes in vegetation covers and again holding everything else constant. We are aware that there is a concern regarding our approach of using the model that we have calibrated at the watershed scale to examine runoff sensitivity at a hillslope scale, but the lack of observed data at hillslope level in our study watershed was the only reason for not calibrating our model at hillslope scale. We are also aware that low coniferous LAI would drive our runoff results that showed lower sensitivity to deforestation of coniferous. We think that this low coniferous LAI values are due to our modelling set-up (low initial LAI used with no verification to high resolution LAI input data). We caution the reader that the results presented in this work should be interpreted as best estimates based on the knowledge incorporated in RHESSys.

The RHESSys model was first calibrated to daily streamflows at the watershed outlet during the 1994 water year. Monte Carlo simulation was used to generate 5000 sample parameter sets from independent uniform distributions over the feasible parameter ranges determined from the literature. Each was used as input to the model, and a group of behavioural parameter sets was selected in terms of the Nash–Sutcliffe metric on daily flows, Nash–Sutcliffe metric on log daily flows and total annual flow error. Variability over the range of calibrated parameter values from this behavioural group was used to quantify sensitivity of runoff to parameter uncertainty.

RHESSys was then used to quantify runoff sensitivity to land cover change in two independent numerical experiments. The first experiment examined the runoff sensitivity at a hillslope with coniferous cover to vegetation changes. These vegetation change scenarios include change to grass, no vegetation and deciduous cover. The second experiment was similar to the first experiment but differed in that the hillslope vegetation cover was deciduous not coniferous. In this second experiment, we changed deciduous vegetation cover to grass, no vegetation and coniferous cover. Each experiment was carried out separately while holding everything else constant.

Our results suggest that the mean annual relative potential evapotranspiration coefficient for deciduous cover is about 0.922 and for coniferous cover is about 0.964. This suggests that coniferous and deciduous vegetation at our study watershed behaves similarly in terms of having evapotranspiration rates limited to available energy only with no limitation due to water availability. This watershed behaviour is also supported by the fact that $\overline{E}_p/\overline{P} < 1$ and $\overline{Q}/\overline{P}$ is so large, which suggests this is an energy-limited watershed from concepts discussed by Budyko (1974). The RHESSys model uses the standard Penman–Monteith (Monteith, 1965) methods to estimate the potential evapotranspiration rate. We looked at other methods and sources to find potential evapotranspiration rate estimates (Deichmann and Eklundh, 1991; Allen *et al.*, 1998; Dingman, 2002). We found that generally RHESSys estimates of potential evapotranspiration rates were aligned with other work that uses the Penman–Monteith method. Table III summarizes evapotranspiration information from the two study hillslopes with deciduous and coniferous vegetation covers as well as estimates of relative evapotranspiration coefficients.

Our results match observations that suggest that in regions where watersheds are dominated by snowmelt, peak flows increase as a result of increased snow accumulations in clearings, as compared with forested areas, and more rapid snowmelt owing to enhanced turbulent energy transfer in harvested areas (Bosch and Hewlett, 1982; Stednick, 1996). This can be inferred from the May average runoff when vegetation cover has been converted to no vegetation.

We are not aware of a field/model study at our study watershed to better verify this work results. Linking our results with field-based research would certainly enhance the quality of our modelling approach and results. Our results need to be interpreted with the physical characteristics associated with our particular hillslopes examined (area in the range of $0.3\,km^2$, mean annual precipitation about 830 mm, elevation about 2600 m and 40.73° in latitude) and with the approximation we have because we are using a model that has not been calibrated at a hillslope level.

It is important to mention that we have examined the sensitivity of our runoff results discussed earlier to uncertainty in calibrated parameters. A group of behavioural parameter sets was selected in terms of the Nash–Sutcliffe metric on daily observed flows, Nash–Sutcliffe metric on log daily observed flows and total annual flow error. Variability over the range of calibrated parameter values from this behavioural group was used to quantify sensitivity of runoff to parameter uncertainty. The different model solutions examined gave slightly different values of runoff estimates with the different vegetation types examined, but the patterns and trends suggested by these different model solutions were essentially the same.

The results of this work cannot substitute for direct field measurements, because models are often uncertain. We agree with Christensen *et al.* (2008) in that model results such as the ones presented in this work should be thought as tools used to efficiently guide field measurements. These models should be considered as best estimate of reality given the knowledge we have about a rich area of research in hydrology, which is hydrological processes. We feel that understanding changes in water yield requires a better knowledge of plant area index, canopy conductance, interception and evapotranspiration. In order to obtain that knowledge in these hydrological processes, extensive field programs intended to examine their sensitivities to climate and land cover changes is needed.

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