SIMULATING LONG-TERM LANDCOVER CHANGE AND WATER YIELD DYNAMICS IN A FORESTED, SNOW-DOMINATED ROCKY MOUNTAIN WATERSHED

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ABSTRACT

Changes in the extent, composition, and configuration of forest cover over time due to succession or disturbance processes can result in measurable changes in streamflow and water yield. Removal of forest cover generally increases streamflow due to reduced canopy interception and evapotranspiration. In watersheds where snow is the dominant source of water, yield increases and advanced peak discharge are attributed to increased snow accumulation, and enhanced melt rates in forest openings. Because knowledge of long-term watershed-level streamflow responses to landcover dynamics is limited by relatively short-term gage data, we present a modeling approach that combines existing vegetation and hydrologic simulation systems to evaluate these interactions. Our findings suggest that both vegetation and hydrologic characteristics of the research watershed are at the limits of their estimated natural ranges. Although species composition remained fairly stable over time, the size and connectivity of current landcover patches are at the upper end of the estimated temporal distribution. The large proportion and continuous nature of forest cover associated with current conditions coincide with water yield, peak discharge rates, and flow variability that are at the low end of their modeled distributions. The integrated modeling approach we describe should be applicable in other ecosystems given knowledge of biophysical interactions and availability of appropriate data. By gaining an understanding of the possible range of variability due to natural conditions, management plans may be designed to maintain resources within estimated and desirable bounds.

INTRODUCTION

Vegetation characteristics are one of the key factors influencing the amount and timing of runoff from forested mountain watersheds. The forest canopy moderates the precipitation-infiltration-runoff continuum by influencing air turbulence patterns, interception, and evapotranspiration, while also providing insulation from incident solar radiation and wind scour (Kimmins, 1997). Timber harvest can result in increased streamflow due to the reduction in canopy interception and evapotranspiration in clearings and stands with reduced density (Golding and Swanson, 1978; Troendle, 1983; Troendle and King, 1985; Troendle and King, 1987; Pomeroy, et al., 2002). Similarly, natural disturbance mechanisms such as fire, insects, and disease affect basin-wide runoff and water yield by periodically thinning or creating openings in the forest canopy (Bosch and Hewlett, 1982; Troendle, 1983; Stednick, 1996). A reduction in the frequency of natural disturbance events due to human intervention or climatic variability may lead to denser stands and an increase in forest area, with a consequent decline in watershed runoff (Farnes et al., 2000). While the hydrologic effects of forest harvest have been widely studied, very little work has been done to determine how natural disturbance processes, and human influences on those processes, may affect the magnitude and the range of variability in runoff and water yield from forested watersheds.

Fire is the primary natural disturbance agent in the Rocky Mountains of western North America (Arno and Fiedler, 2005). Since the early 1930s, fire suppression programs in the United States and Canada have attempted to curtail the occurrence of fire in the region, and evidence suggests that there has been a concurrent increase in the extent, continuity, and density of forested stands, and an invasion of shrubs and trees into grasslands (Keane et al., 2002). Presumably, these changes in the disturbance regime and associated change in vegetation characteristics have affected watershed runoff. Evaluating the effect of these changes in forest structure on runoff and water yield requires understanding of the natural range of variability in vegetation conditions and hydrologic response. However, even the longest stream flow records are shorter than the 100-400 year natural fire return intervals in the region's high elevation forests, and there are no stream flow records from the period prior to European settlement. Evaluating the natural range of variability in watershed runoff from forested watersheds in the Rocky Mountain region therefore depends on the use of models capable of simulating conditions at time scales of many hundreds of years. In this paper we present a modeling approach that uses a 300-year simulation of vegetation dynamics to

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provide land cover data for a watershed scale hydrologic simulation model. We use this approach to compare the current hydrologic response of a forested, snowmelt dominated, Rocky Mountain watershed to the range of variability that would occur given an unmanaged long-term vegetation scenario that encompasses the region's approximate 100-400 yr. fire cycle (Arno and Fiedler, 2005).

Vegetation dynamics were modeled with SIMPPLLE (Simulating Patterns and Processes at Landscape Scales). SIMPPLLE is a regionally calibrated vegetation dynamics simulation system that models the long-term impact of landscape management over large areas (Chew et al., 2002) at annual or decadal time-steps. SIMPPLLE integrates data from a diversity of sources. Vegetation is defined by stand-level inventory data whenever possible, but algorithms have been developed to extract the necessary information from classified satellite imagery when full coverage is otherwise not available. Management logic, environmental conditions, and physiognomic data (Pfister et al., 1977) in combination with dominant stand species, size class, and canopy density information are used to advance vegetation through calibrated pathways and conditional probabilities to simulate succession, and natural and planned disturbances over periods of up to 500 years (Chew et al., 2004). Simulations derived from SIMPPLLE are presently being used by the Northern Region of the USDA Forest Service to assess forest management alternatives (Barrett, 2001).

Hydrologic modeling was conducted using the Soil and Water Assessment Tool (SWAT), a physically based, distributed, continuous, river basin model developed to predict the impact of land management practices on hydrologic processes in potentially large, complex watersheds with varying soils, landcover and management practices (Arnold et al., 1998; Srinivasan et. al., 1998; Di Luzio et. al., 2004). The model runs on a daily time step, and hydrologic processes represented include snow accumulation and snowmelt, interception, evapotranspiration, surface runoff, soil percolation, lateral and groundwater flow, and river routing. Model configuration can be achieved using topographic, soil, landcover and climate data available from government agencies worldwide, although more detailed information can also be included. The model partitions a watershed into subbasins, river reaches and Hydrologic Response Units (HRUs). Subbasin delineation provides the spatial context, while further sub-division into HRUs is done in a statistical manner by considering a certain percentage of landcover and soils in a subbasin, without any specified location in the sub-basin (Neitsch et. al., 2002).

The SIMPPLLE model was used to project current vegetation conditions forward at a decadal time-step, for 300 years, across the Little Belt Mountains of central Montana. Simulated vegetation was reclassified into generalized landcover categories and used to drive the land-phase of the SWAT hydrologic model for the Upper Tenderfoot Creek research watershed, which lies at the core of the Little Belt Mountain range (Figure 1). Patterns of predicted landcover proportions, configuration, and associated streamflow responses were analyzed and compared to current conditions. Application of this procedure provides a means for establishing the range of probable watershed conditions and places the current conditions in the context of possible conditions over time. With sufficient data and ecological understanding, this approach should also be applicable in other biomes. By gaining an understanding of the possible range of variability due to natural conditions, management plans may be designed to maintain resources within the estimated and desirable bounds.

STUDY AREA

The Upper Tenderfoot Creek research watershed lies within the Tenderfoot Creek Experimental Forest (McCaughey, 1996), on the west slope of the Little Belt Mountains in central Montana, USA (Figure 1). This broad basin-like watershed is oriented to the northwest, and bisected by a steep canyon along the main channel. An upper reach and two major tributaries on each north and south aspects make up the 2,251 ha that contribute flow to the main outlet.

The watershed is underlain by Precambrian age sedimentary rocks of the Belt Supergroup (Alt and Hyndman, 1986). The most extensive soil groups are loamy skeletal, mixed Typic Cryochrepts and clayey, mixed Aquic Cryoboralfs (Farnes et al., 1995).

Several large (800 to 1,500 ha) fires have occurred in the watershed over the past four centuries but nearly 120 years have elapsed since the last major stand replacing fire (Barrett, 1993). Forest stands of varying developmental stages presently cover 85% of the watershed. Approximately 65% of the watershed is composed of lodgepole pine (*Pinus contorta*), which generally represent the most recently initiated stands. Over time, shade tolerant subalpine fir (*Abies lasiocarpa*) and Englemann spruce (*Picea engelmannii*) emerge underneath decadent pine and now make up about 20% of the landcover. Decadent, low-density and disturbed stands constitute another 11% of the watershed. The remaining 4% of the watershed consists of shrubby meadows and small riparian areas along creek bottoms (1%), drier grasses on higher ground (1%) and talus slopes (2%).

Climate patterns are continental, and almost 70% of the 800mm mean annual precipitation is deposited as snow between October and April. The annual peak discharge, driven by snowmelt, occurs between mid-May and early June, while the low flow period begins in August and persists through April. The mean annual water yield from the upper Tenderfoot Creek watershed is approximately 400 mm.

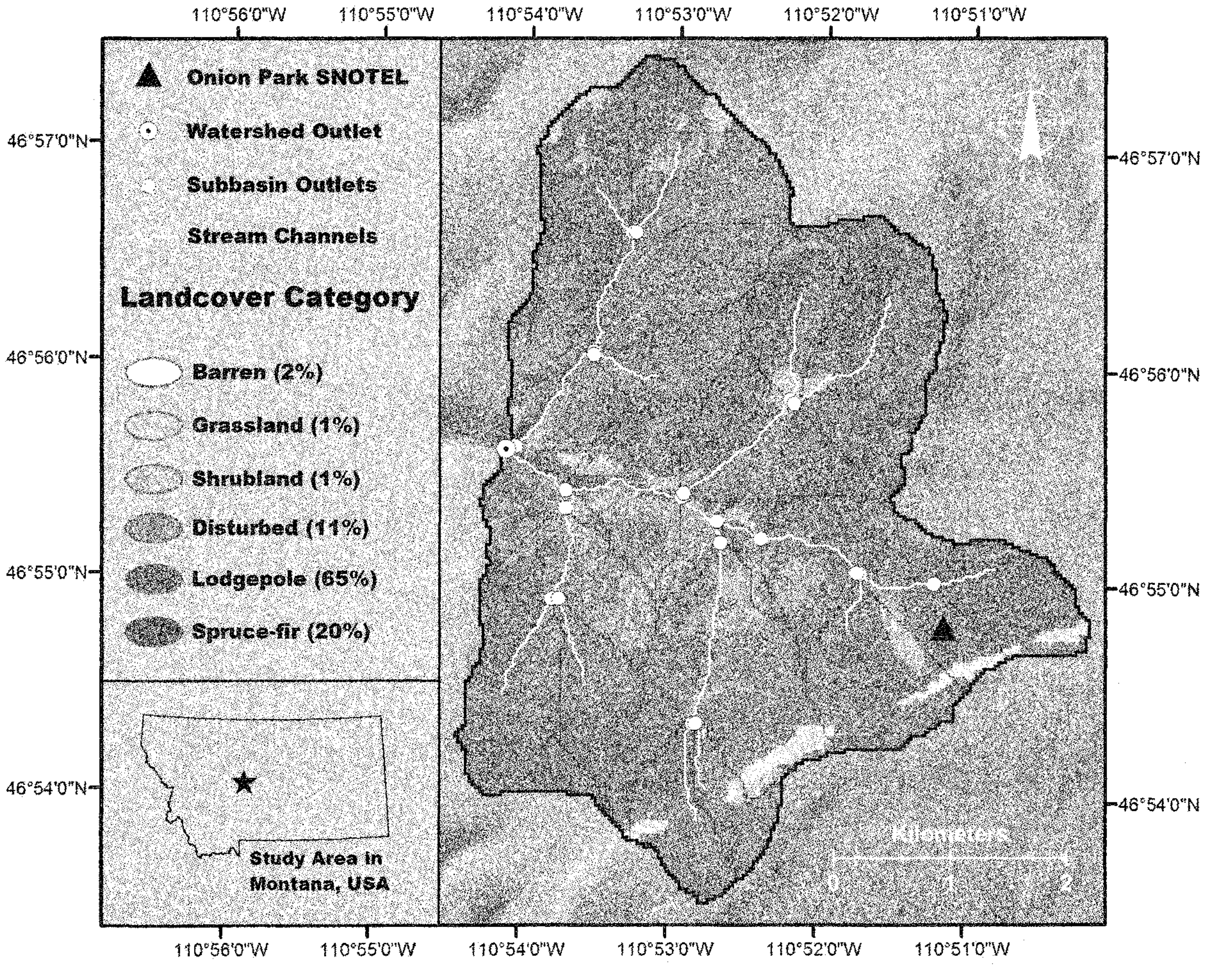

Figure 1. The upper Tenderfoot Creek research watershed, with location in Montana, USA, denoted by the inset map.

METHODS

Landcover Simulation

The SIMPPLLE model has the capability to simulate both managed and unmanaged vegetation dynamics. Since the goal of the study was to determine the range of variability in the absence of human disturbance, the model was run forward in time once for 300 years at decadal time steps, assuming an unmanaged scenario and starting with the current landscape cover characteristics. The simulation encompassed the entire Little Belt mountain range so that disturbance process propagation into the research watershed from the surrounding landscape was accounted for. For every stand, SIMPPLLE characterized species composition, size-class, and canopy density, and used biophysical input data, user-specified logic, and conditional probabilities to stochastically advance each stand in the landscape through states of succession and disturbances processes at the time-step of the model. Because state advancement is probabilistic, multiple simulations can be initiated to capture the potential range of vegetation characteristics over time. Zuuring and Sweet (2000) have shown that output from 30 to 100 iterations tends to be normally distributed and can be described with parametric methods (Ott, 1993). We developed an algorithm that captured the ecological processes of the model, reclassified the multi-dimensional vegetation output for each stand, and produced grid-based maps with 30 m pixel resolution that represent vegetation as generalized landcover at every time-step (Figure 2). The classes produced by the algorithm closely resemble the Level II landcover categories developed by the United States Geological Survey (Anderson et al., 1976), but have been refined to include more detailed differentiation among forest types.

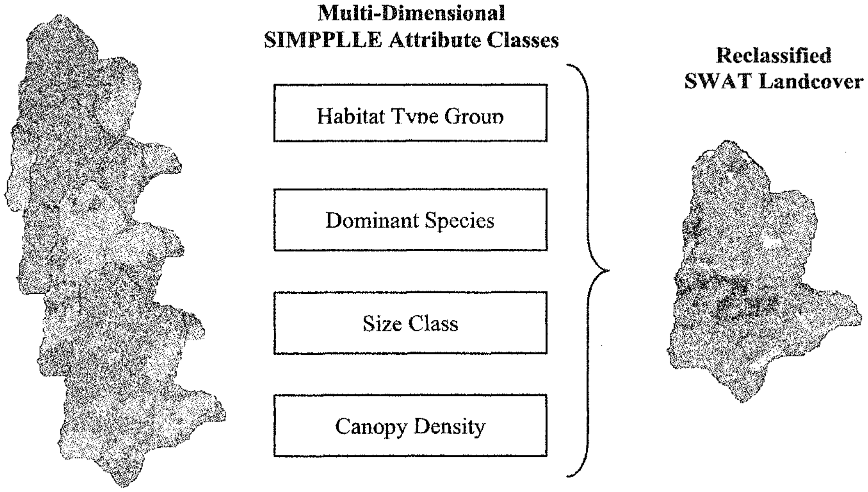

Figure 2. A diagram of the reclassification algorithm used to convert multi-dimensional stand attributes produced by the SIMPPLLE vegetation simulator into generalized landcover categories.

Each landcover category created by the reclassification was attributed with regionally estimated maximum canopy height (m), seasonal effective maximum and minimum leaf area index (LAI; m^2/m^2) derived through remote sensing (Hall et al., 2003), relative annual interception capacity based on field measurements (Moore and McCaughey, 1997; McCaughey and Farnes, 2001; Woods et al., 2004), base temperature for the onset of productivity (c), Manning's roughness coefficient, *n*, for overland flow (Neitsch, 2002), and SCS curve numbers for soil type B (USDA-SCS, 1972) for use in hydrologic modeling.

Evaluation of Simulated Landcover

The categorical relative watershed distribution and spatial pattern of simulated landcover was quantified for each of the 30 reclassified time-series maps, and compared to that of the current mosaic. These evaluations show how the composition and structure of the current landscape compares to the modeled range of natural variability.

To assess landcover composition, relative areas occurring currently were compared to the central tendency, and variation of areas occupied by each category over the course of the long-term simulation.

Quantification of patterns can be an important component of landscape evaluation and management (Farina, 2000) because landscape configuration can generally be related to ecological processes (Forman and Gordon, 1986; Zonneveld and Forman, 1990). Many metrics have been developed that describe the proportions and configuration of patches, classes of patches, and landscape-level system properties (McGarigal and Marks, 1995). Because each metric measures a specific characteristic of heterogeneity, simultaneous consideration of several indices is often instructive (Gustafson, 1998). Three landscape-level indices were used to describe proportions, aggregation, and connectivity of the current and simulated vegetation mosaic over time. The Largest Patch Index (LPI) measures the percentage of total landscape area comprised by the largest patch. Landscape Shape Index (LSI) values can be interpreted as a measure of patch aggregation; as LSI increases, patches become increasingly disaggregated. Lastly, the Contagion Index (CONTAG) provides an assessment of overall landscape clumpiness. When Contagion is high, large clumps exist (Turner et al., 1989; McGarigal and Marks, 1995)

Calibrating Hydrologic Output to Current Landcover

The 2,251 ha drainage was configured with 22 subbasins, and 54 unique combinations of subbasin, landcover and soil types, referred to as hydrologic response units (HRUs). SWAT was calibrated for streamflow using spatially explicit current landcover characteristics, soil characteristics defined by the Montana STATSGO dataset (USDA-NRCS, 1994), and four years of daily temperature, precipitation, and streamflow data. Climate data were obtained from the Onion Park snow telemetry site (SNOTEL) located within the research watershed. Streamflow data from a flume at the watershed outlet were used for calibration and subsequent model validation.

The configured and initially parameterized SWAT model was used to simulate the period from January 1, 1993 to December 31, 2002. The first two years of the simulation were used to spin up the model and allow it to equilibrate to ambient conditions (White and Chaubey, 2005).Years 1997 through 2000 were used for model calibration, and model validation was performed by running the calibrated model for the two years prior to (1995-96) and two years beyond (2001-02) the calibration period (Table 2). The time period used for model calibration and validation encompassed a wide range of environmental conditions, including wet, dry and average years. Despite being a fairly short period of time, research into calibration data requirements has shown that information richness of this type is more valuable than lengthy records alone (Gupta et al., 1998).

Table 2. Hydrologic simulation timeline

Spin-Up		**Validation**		**Calibration**				**Validation**	
1993	1994	1995	1996	1997	1998	1999	2000	2001	2002

Model performance was assessed with time-series and scatter plots, in conjunction with a variety of commonly used evaluation statistics (Coffey et al., 2004; White and Chaubey, 2005). The model was first calibrated by minimizing the relative error (RE) between measured and simulated precipitation, snowmelt, and water yield. Further model refinement focused on matching the simulated timing of streamflow to measured monthly and daily values through iterative parameter adjustments that optimized the Nash and Sutcliffe (1970) coefficient (NS), liner regression coefficient (R^2), root mean square error (RMSE), average percent deviation (D_v), and model bias. NS is a sum of squares relative model efficiency measure that has been recommended by the American Society of Civil Engineers for gauging hydrologic model performance (Coffey, et al., 2004), and we therefore focused our interpretation of results on it. Values of the coefficient can range from negative infinity to a high of 1, which corresponds to a perfect fit between measured and simulated data. This statistic can be negative because actual, not absolute, differences are used to calculate it. When coefficient values are 0 or less, model predictions are no better than the mean of observed data. NS is calculated as:

$$NS = 1 - \left[\frac{\sum (\hat{y} - y)^2}{\sum (y - \bar{y})^2} \right]$$

where individual and mean measured values are y and $\bar{y}$, and simulated values are $\hat{y}$ and $\bar{\hat{y}}$, respectively

A global sensitivity analysis was conducted at the onset of the calibration procedures to identify influential parameters (van Griensven et al., 2006). Following calibration, partial model sensitivities were quantified by resetting, in turn, the snow, soil, surface runoff and groundwater parameter groups to their default values, and running the model with the other parameter groups in their calibrated state. Output from each partially calibrated model run was compared to the fully calibrated model, and relative NS differences were computed.

Hydrologic Assessment of Long-term Landcover Change

The calibrated SWAT model was used to simulate streamflow in response to each of the 30, 10-year time-step landcover maps. For every 10-year representation of landcover, SWAT was run from 1993-2002 using the same watershed configuration, soil and climate forcing data to ensure that streamflow variability can be unambiguously attributed to changes in landcover. To further isolate hydrologic response due to landcover dynamics, output from a single year that represented typical climate and hydrologic patterns (1999) was used in the evaluation procedures. Daily hydrographs were constructed for each landcover representation to show the range of streamflow responses to varying vegetation patterns. With values from each representation, a composite hydrograph of mean daily streamflow was plotted against the hydrograph of calibrated conditions to illustrate how current streamflow relates to central tendency of a range of possible patterns. Time-series annual water yield, peak discharge rate and flow regime variability were also assessed and compared to current conditions.

RESULTS

Landcover Patterns

Vegetation dynamics modeled with SIMPPLLE indicated that, under an unmanaged scenario, the Tenderfoot Creek research watershed would have considerably less mature forest cover, more disturbed forest, and a greater area of shrublands than at present. In addition, under the current conditions, many of the dominant vegetation cover types within the Tenderfoot Creek research watershed are either at the limit or outside of the natural range of variability. Total forest cover, which is presently 85% of the watershed, is nearly twice as high as the long term mean of 46%. Present day values for both lodgepole pine (65%) and spruce fir forest (20%) are more than two standard deviations from the simulated long term means of 41% and 5%. Shrublands, which presently encompass only 1% of the watershed, would average 19% under natural conditions, so that current conditions are more than two standard deviations below the mean. The only general landcover category that is similar under both the current and simulated unmanaged conditions is grassland, which encompasses only about 1% of the watershed.

The largest patch index (LPI) for the current landscape is more than two standard deviations above the mean, indicating that landscape patches are much larger than would occur across most of the range of conditions in an unmanaged landscape (Table 3 and Figure 3b). Similarly, the current landscape shape index (LSI) is more than two standard deviations below the mean, and the contagion index is nearly two standard deviations above the mean, indicating that under an unmanaged scenario landscape vegetation patches would be more disaggregated and less clumpy than they are at present.

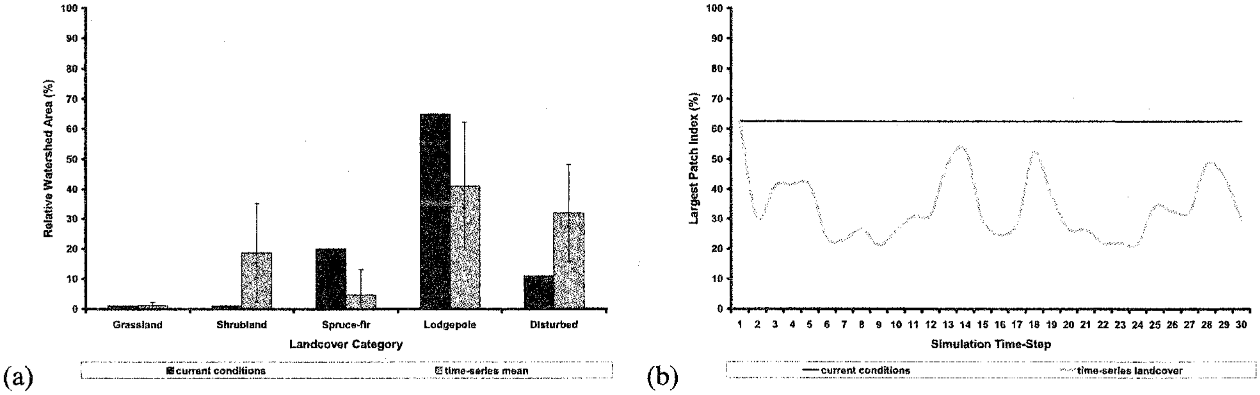

Figure 3a, b, and c. Comparison of relative watershed area occupied by the current and mean times-series landcover categories. Error bars represent ± two standard deviations of the mean, capturing the full range of data (a). Comparison of the landscape-level Largest Patch Index (LPI) that describes the current and simulated landcover configuration in the research watershed. The straight line illustrates the metric's current value while the undulating, line depicts time-series values.

Table 3. Summary statistics for largest patch index (LPI), Landscape Shape Index (LSI) and Contagion (CONTAG) for the current mosaic and simulated unmanaged conditions over 300 years of simulation at decadal time steps.

Landscape Metric	Current	Mean	Stdev	Min	Max
Largest Patch Index (LPI)	62.61	33.77	10.96	21.20	62.61
Landscape Shape Index (LSI)	7.23	8.88	0.77	6.82	9.69
Contagion (CONTAG)	62.50	55.17	3.99	49.35	64.33

Hydrologic Model Calibration and Validation

The calibrated SWAT model simulated daily streamflow with a Nash-Sutcliffe (NS) efficiency of 0.86 and predicted 98% of the measured water yield over the calibration time period (Table 4, Figure 4). In the subsequent validation run the model simulated daily streamflow with a NS efficiency of 0.80, and produced 96% of the measured water yield.

Table 4. Hydrologic calibration and validation statistics for annual, monthly and daily streamflow (cms) where RE refers to relative error, NS is Nash-Sutcliffe model efficiency, R^2 is the linear correlation coefficient, RMSE is root mean square error, Bias, and D_V is the mean relative difference between simulated and observed streamflow.

Simulation Type	**RE**	**NS**	**R^2**	**RMSE**	**Bias**	**Dv**
Annual Default (1997-2000)	5	0.82	0.91	43.13	21.89	8
Annual Calibration (1997-2000)	2	0.90	0.91	33.17	-9.60	4
Annual Validation (1995-96, 01-02)	4	0.88	0.94	38.47	-16.86	7
		NS	**R^2**	**RMSE**	**Bias**	**Dv**
Monthly Default (1997-2000)		-0.02	0.27	47.40	1.83	84
Monthly Calibration (1997-2000)		0.89	0.93	16.61	-0.80	31
Monthly Validation (1995-96, 01-02)		0.89	0.92	16.51	-1.39	31
		NS	**R^2**	**RMSE**	**Bias**	**Dv**
Daily Default (1997-2000)		-2.31	0.03	0.87	0.02	109
Daily Calibration (1997-2000)		0.86	0.89	0.19	-0.01	35
Daily Validation (1995-96, 01-02)		0.80	0.82	0.25	-0.01	42

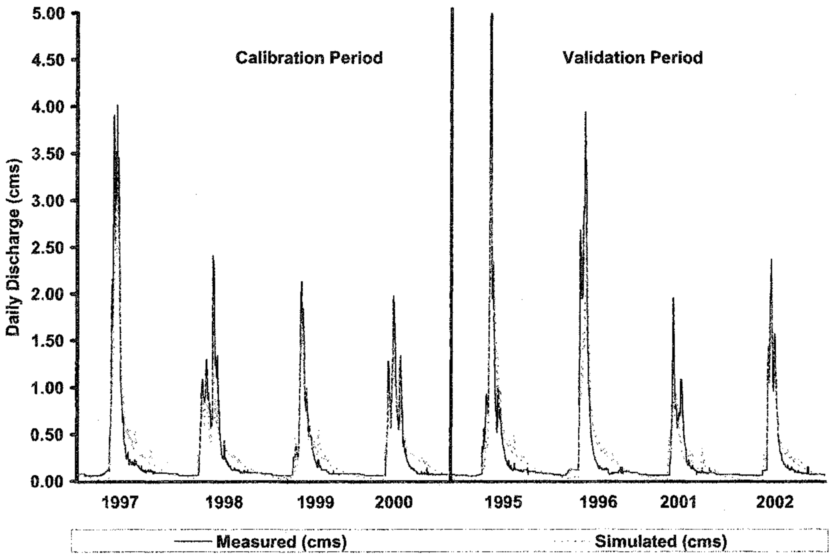

Figure 4. Simulated mean daily discharge during calibration (1997-2000) and validation (1995-96, 2001-02)

A global sensitivity analysis indicated that streamflow calibration was strongly affected by parameters that govern snow processes, surface runoff, groundwater, and soil properties. Snow process parameters included snow fall and melt temperature, minimum and maximum melt rates, a snow pack temperature lag factor, and two snow cover depletion factors. Surface runoff was calibrated with the surface runoff lag coefficient, (*surlag*). Groundwater recharge time, a baseflow recession constant, and deep aquifer percolation fraction parameters were used to for groundwater process calibration. Soil processes were adjusted by altering the available water content and saturated hydraulic conductivity parameters.

Post-calibration, parameter set decomposition clearly illustrated that, relative to others, snow accumulation and melt processes had the strongest influence on model performance, followed by surface runoff, groundwater, and soil parameters (Table 5, Figure 5a, b, c, and d).

Table 5. Parameter set sensitivity analysis diagnostic statistics, 1999 daily streamflow (cms)

Parameter Set	NS	R^2	RMSE	Bias	Dv	NS diff (%)
Fully calibrated model	*0.92*	*0.93*	*0.11*	*0.00*	*29.82*	
default snow	-0.06	0.08	0.40	-0.02	83.09	106.41
default surface runoff	0.19	0.43	0.35	0.00	62.20	79.12
default groundwater	0.80	0.81	0.17	0.02	51.95	12.54
default soil	0.88	0.91	0.14	0.02	37.07	4.36

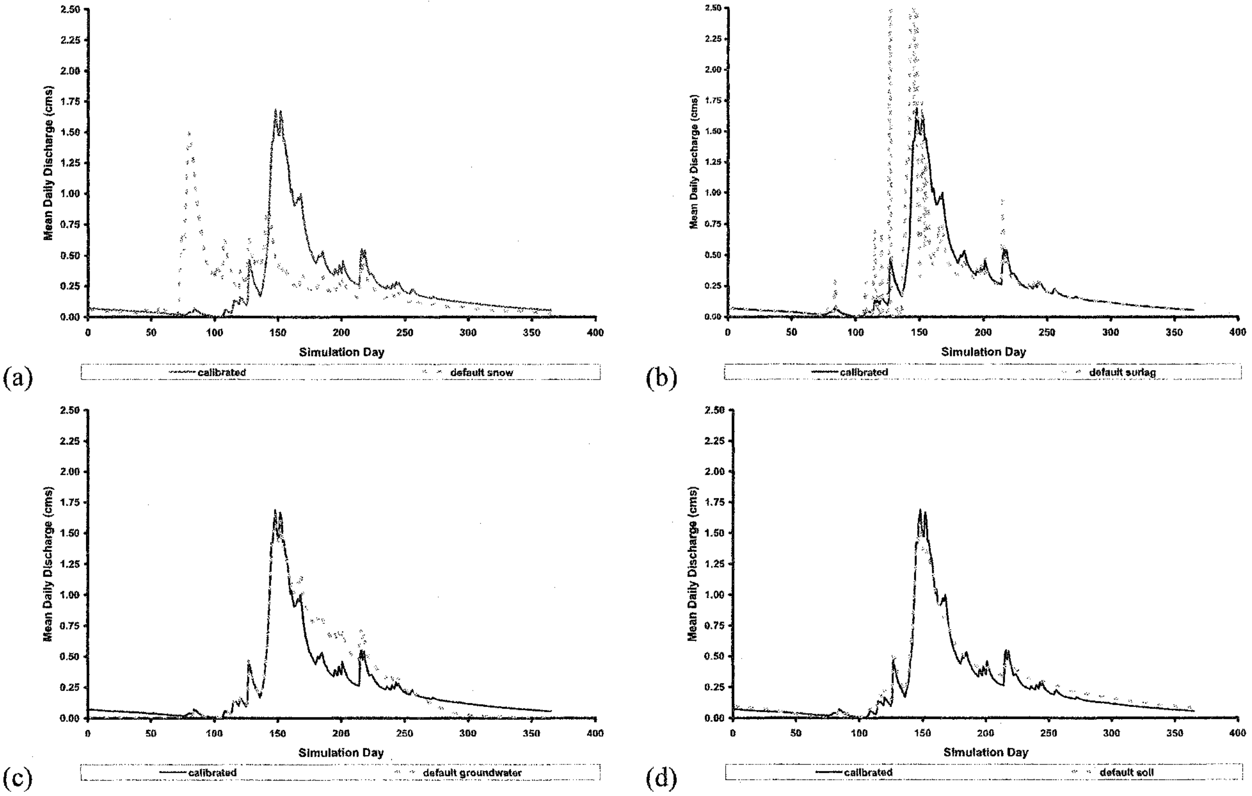

Figure 5a, b, c, and d. Results of partial sensitivity analyses. Solid line indicates fully calibrated model and dashed line indicates model output using default parameter sets for (a) snow processes (b) surface runoff (c) groundwater and (d) soil parameter sets in a representative year, 1999.

Time-Series Hydrologic Variability

Over the range of simulated landcover scenarios, peak flow rates for the modeled water year (1999) varied approximately 12%, from 1.70 to 2.19 cms, while variation in annual yield varied 4% from 337 to 349 mm (Figure 6a). Compared to current conditions, the time-series model yielded between 1.5% and 4% more water annually, and annual peak flow rates were up to 22% greater in magnitude. Time-series landcover scenarios were associated with streamflow patterns that had, on average, 5% greater discharge rates, and the median flow between the 95-99th percentile was about 10% larger (Figure 6b).

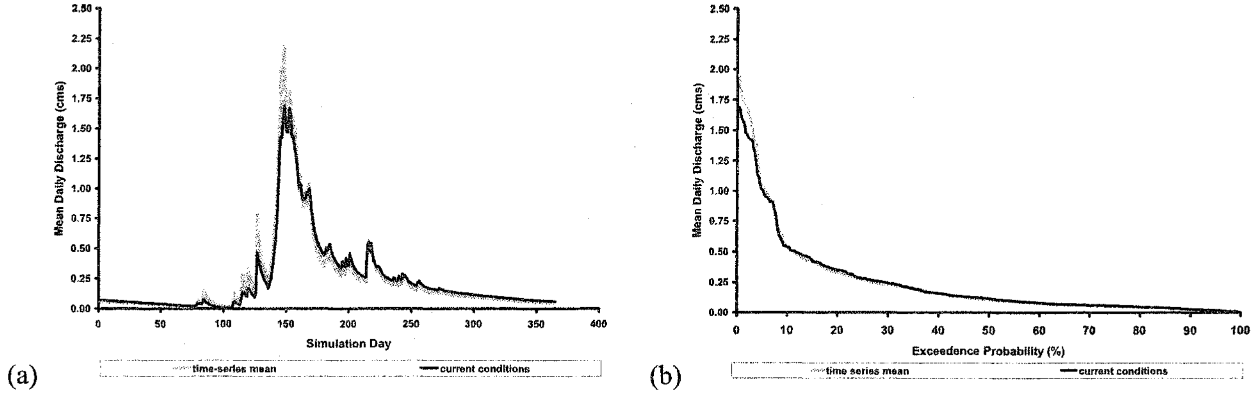

Figure 6. Simulated streamflow range (min and max) associated with the time-series landcover, plotted against current values (a), and mean time-series streamflow exceedence probability relative to current streamflow (b)

DISCUSSION

Much of the water that supplies western North America originates as snow that is deposited and temporarily stored in forested mountain watersheds. The high value of water resources has encouraged nearly a century of research focusing on the relationships between conifer forest characteristics and their influence of the magnitude and timing of basin-wide runoff. This work has shown removal of threshold levels of forest cover, tends to advance the timing of snowmelt runoff, increase the magnitude of peak flows, and elevate total annual water yield. Similarly, when undisturbed for long periods of time, the process of succession may increase the extent of forest cover, and cause stands to become denser. Relative to other types, conifer forests intercept more precipitation and transpire more water, and increased relative abundance of this landcover can therefore lead to reduced watershed runoff.

While the interactions between forest and hydrologic characteristics have been well documented, the dynamic range over which this relationship occurs naturally is less well known. Fire is the dominant disturbance agent that imparts changes to the mosaic of Rocky Mountain forests, but our ability to empirically evaluate the interactions between varying vegetation patterns and watershed-level streamflow response is limited by the relatively short duration of continuous streamflow measurements in upland watersheds. Most gage records only reflect an 80 year history, but estimated fire cycles range between 100 – 400 years. Over the period of measurement relatively few large watershed-altering forest fires have been observed. Regardless of whether this is because of effective suppression efforts or an intrinsically low probability of occurrence (Strauss, 1989), we do not have sufficient data to estimate the natural range of streamflow variability in forested mountain watersheds. Using current knowledge of watershed processes, we have developed a modeling framework to ascertain a potential range of streamflow variability in forested mountain watershed, based on a natural, long-term vegetation dynamics scenario.

Landscape Vegetation Dynamics

Vegetative state advancement in our simulations of landcover change using the SIMPPLLE model is based on succession pathways and disturbance probabilities related to stand characteristics including history, topology, habitat type, composition and structure. The relationships used in the model have been defined by scientists across the Northern Region of the USDA Forest Service (R1), and represent the current state of knowledge.

The stochastic structure of the model makes it possible to estimate the range of vegetation conditions over time by running multiple simulations of a defined landscape over short periods, or individual long-term simulations. To estimate the range of landcover patterns, we ran a single simulation that spanned a 300 year time frame, and encompassed the probable fire cycle of this region. Using a decadal time step, our procedure yielded a set of 30 time-series landcover maps.

Simulated patterns of landcover composition and configuration, measured by relative abundance and landscape-level spatial pattern metrics, appear to be cyclical and punctuated by rare but large fluctuations. Assessment of fire history in the research watershed estimated roughly 4 distinct episodes over a period of roughly

400 years that disturbed more than 25% of the area (Barrett 1993). Analysis of the predicted landcover shows a pattern of disturbance that is quite similar, where large changes in forest extent and configuration are evident approximately 3 times over the 300 year simulation period. We therefore feel that our landcover simulations portray a level of landcover stochasticity that is similar to what has been observed through ancillary data, and resulting maps span the potential range of conditions likely to occur in the research watershed over time. The distribution of values from these maps, thus, provides the context in which we assess current watershed landcover patterns and associated hydrologic characteristics.

The existing landcover mosaic in the research watershed has been influenced by nearly 120 years of relatively disturbance free succession. Due to biophysical variables and a fairly long time since disturbance almost 85% of this watershed is covered by coniferous forest, composed largely of lodgepole pine (*Pinus contorta*), subalpine fir (*Abies lasiocarpa*) and Engelman spruce (*Picea engelmannii*). When compared to time-series distributions of landcover composition and configuration, it is clear that current patterns are at the limit of their estimated ranges.

In terms of composition, when the relative abundance of landcover categories was averaged over the simulation period, mature forest was reduced by 45%, and generally replaced by shrubland and disturbed forest cover types. The current proportions of forest cover types exceed the distribution of their simulated abundance. Conversely, the abundance of shrubland, and disturbed forest is currently lower than predicted over time.

Assessment of landcover configuration also shows that current patterns are at the extreme ends of the simulated distributions. Compared to time series values, the current landcover pattern is characterized by larger, more aggregated, and clumpy patches. Of all the metrics evaluated, LPI may be the most informative. For maps classified into categories of suitable and unsuitable patches (i.e. forest and nonforest) the primary determinant of spatial pattern is proportion of the class of interest (Gustafson, 1998). The compositional component determines the probable range of many patch configuration characteristics. If proportion is low, generally the patches are small and isolated, and do not have enough area to form convoluted shapes.

According to percolation theory (Stauffer, 1985), if a suitable habitat patch (i.e. forest) occupies 59% of the landscape, then a process such as fire may easily spread across the entire landscape (Turner et al., 1989). The largest patch in the existing landscape occupies 62% of the watershed, and furthermore, 85% of current landcover is composed of mature forest. The combination of composition and configuration creates a situation that is highly conducive for propagation of fire across the watershed. If the simulated patterns are an indication of this watershed's landcover trajectory, it plausible that a large stand replacing disturbance is likely to occur in the future. Major changes in landcover composition and structure have the potential to alter the watershed hydrologic response.

Watershed Response to Vegetation Change

Simulated streamflow was calibrated to the current landcover conditions, using regionally derived estimates of important hydrologic parameters. The final model seems to produce results that are well within the range of what other modeling studies have reported. A review of contemporary literature by White and Chaubey (2005) lists NS values ranging between 0.76 – 0.98 for annual, and 0.58 – 0.98 for monthly yield estimates. Eckhardt and Arnold (2001) used automated methods and achieved daily values of 0.70 for a small forested watershed in Germany. In our calibration, we obtained annual, monthly and daily NS values of 0.90, 0.89, and 0.86, respectively. Validation of the model, using independent data suggested that the calibration was robust, as reduction in performance was negligible. Despite good overall performance statistics, the model seemed to most accurately represent the snowmelt runoff portion of the hydrograph, while matching low flows was much more problematic.

A global sensitivity analysis of the uncalibrated model identified parameters that govern snow processes, surface runoff, groundwater, and soil properties as highly influential components of the streamflow simulation. Setting each of these parameter sets back to their default values and running the otherwise calibrated model enabled us to quantify their partial sensitivities. Results clearly show that in this forested mountain watershed, parameters that estimate snow fall, accumulation, and melt rates have at least 20% more influence of model performance than other evaluated parameter sets. This may in part explain why seasonal model results were better for runoff rather than baseflow periods. Without the recent incorporation of enhanced snow process routines, streamflow calibration in a snow-dominated watershed, such as ours, may have been less successful (Fontaine et al., 2002).

Running the calibrated hydrologic model separately with each of the 30 landcover representations produced an envelope of streamflow responses that we used to estimate the range of streamflow variability, given landcover change over the course of natural disturbance cycles in this watershed. Streamflow predictions related to our simulations of landcover change appear to be similar to those reported by catchment studies in other parts of the world, and especially in the Rocky Mountain region.

Matheussen et al. (2000) simulated the change between current and historic landcover and hydrologic response and found that forest reduction increased water yield 1-7% in the Columbia River Basin. Recognizing vast differences in scale, results from our simulations are comparable, with annual water yield increase between 1.5 -4.0%. Experimental manipulation in watersheds located in Colorado and Wyoming showed an average increase of 23% in peak flow rates as a result of removing 50% of the forest (Troendle and King, 1985), and an 8% increase due to 24% forest reduction (Troendle et al., 2001), respectively. On average, simulated landcover in our watershed was represented by about 45% less forest and peak flow rates varied 12%, and increased up to 22% over calibrated conditions. Additionally, analysis of daily flows from 28 paired watershed experiments showed that the median increase in the 95-99th percentiles of daily flows was about 10-15% (Austin, 1999). A comparison of current to time-series flow duration shows a very similar trend, where the median difference between the same percentile range is roughly 10%.

Given that our simulations are reasonable, it appears that current landcover and streamflow patterns are at the extreme ends of their probable distributions, and a long-term perspective that encompasses natural cycles is necessary to capture the range of possible conditions likely to occur in the watershed. Currently, forest covers more area than it tends to over time and it seems only a matter of probability before its extent is reduced by cyclical disturbances. Hydrologic patterns observed currently resemble annual yield and peak flow rate values at low end of the estimated range of variability. Temporal landcover change associated with natural disturbances such as fire, insect and disease outbreaks may cause annual water yield and peak discharge rates to fluctuate up to 4% and 12%, respectively. Compared to current conditions, forest cover may be reduced by up to 45%, and this could increase annual water yield between 1.5 and 4% annually, while also increasing peak flow rate by up to 22%.

CONCLUSIONS

Long-term simulations of landcover change indicate that natural disturbances create landcover patches that are smaller, less aggregated, and less contagious than current patterns. Over time, forest cover also tends to occupy less area than it does currently. These simulations also illustrate that patterns of landcover compositions and configuration are cyclical, and periodic disturbances, while they are rare create major changes in landscape mosaic. With a low probability of occurrence, a temporal perspective that encompasses natural disturbance cycles is necessary to capture the range of possible conditions.

The hydrologic model used to simulate streamflow response to landcover change was well calibrated for conditions in this Rocky Mountain watershed, and its performance was most strongly influenced by parameters that govern snow accumulation and melt, relative to other important parameters that describe surface runoff, groundwater or soil characteristics. The incorporation of improved snow process algorithms in the recent versions of the model is therefore likely to encourage its use in other snow-dominated watersheds.

When compared to other published studies of streamflow response to landcover change, our integrated modeling approach appears to produce reasonable results. Interpretation of our results suggests that when landcover patterns are regulated by natural processes over time, and forest cover is reduced, annual water yield may increase by up to 4%, and peak flow rates may be up to 22% greater when compared to current watershed conditions. Using the approach we have described, similar assessments may be conducted in other regions.

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