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Hydrology and water quality in two mountain basins of the northeastern US: assessing baseline conditions and effects of ski area development†,‡

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Abstract

Mountain regions throughout the world face intense development pressures associated with recreational and tourism uses. Despite these pressures, much of the research on bio-geophysical impacts of humans in mountain regions has focused on the effects of natural resource extraction. This paper describes findings from the first 3 years of a study examining high elevation watershed processes in a region undergoing alpine resort development. Our study is designed as a paired-watershed experiment. The Ranch Brook watershed (9·6 km^2) is a relatively pristine, forested watershed and serves as the undeveloped 'control' basin. West Branch (11·7 km^2) encompasses an existing alpine ski resort, with approximately 17% of the basin occupied by ski trails and impervious surfaces, and an additional 7% slated for clearing and development. Here, we report results for water years 2001–2003 of streamflow and water quality dynamics for these watersheds. Precipitation increases significantly with elevation in the watersheds, and winter precipitation represents 36–46% of annual precipitation. Artificial snowmaking from water within West Branch watershed currently augments annual precipitation by only 3–4%. Water yield in the developed basin exceeded that in the control by 18–36%. Suspended sediment yield was more than two and a half times greater and fluxes of all major solutes were higher in the developed basin. Our study is the first to document the effects of existing ski area development on hydrology and water quality in the northeastern US and will serve as an important baseline for evaluating the effects of planned resort expansion activities in this area. Published in 2007 John Wiley & Sons, Ltd.

Key Words alpine hydrology and water quality; ski areas; snowmaking

Introduction

Mountain regions throughout the world face intense development pressures, a concern that has recently drawn national and international attention (Price and Messerli, 2002; Williams, 2002; Stein *et al.*, 2005). Although these development pressures are often associated with recreational and tourism uses, much of the research on bio-geophysical impacts of humans in mountain environments has been focused on the effects of natural resource extraction (e.g. forestry, mining). While analogous in some respects, development of mountain regions for recreation and tourism may be expected to produce effects that differ from those produced by resource extraction. In particular, recreation and tourism may result in higher concentrations of humans in developed settings and a more extensive and denser network of buildings and infrastructure that are intended to persist over time.

The mountain landscape of the northeastern US is one region facing such intense development pressure. More than 40 million people live within one day's drive of the Northern Forest, a region spanning the northern tier of New England and New York and southeastern Canada (Harper *et al.*, 1990). The mountain settings of the region draw recreational users who engage in a variety of activities including leaf peeping, fishing, boating, and skiing. To meet these recreational demands and attract a greater share of the recreational market, many alpine resorts in the northeastern US are undergoing major expansion in an attempt to compete

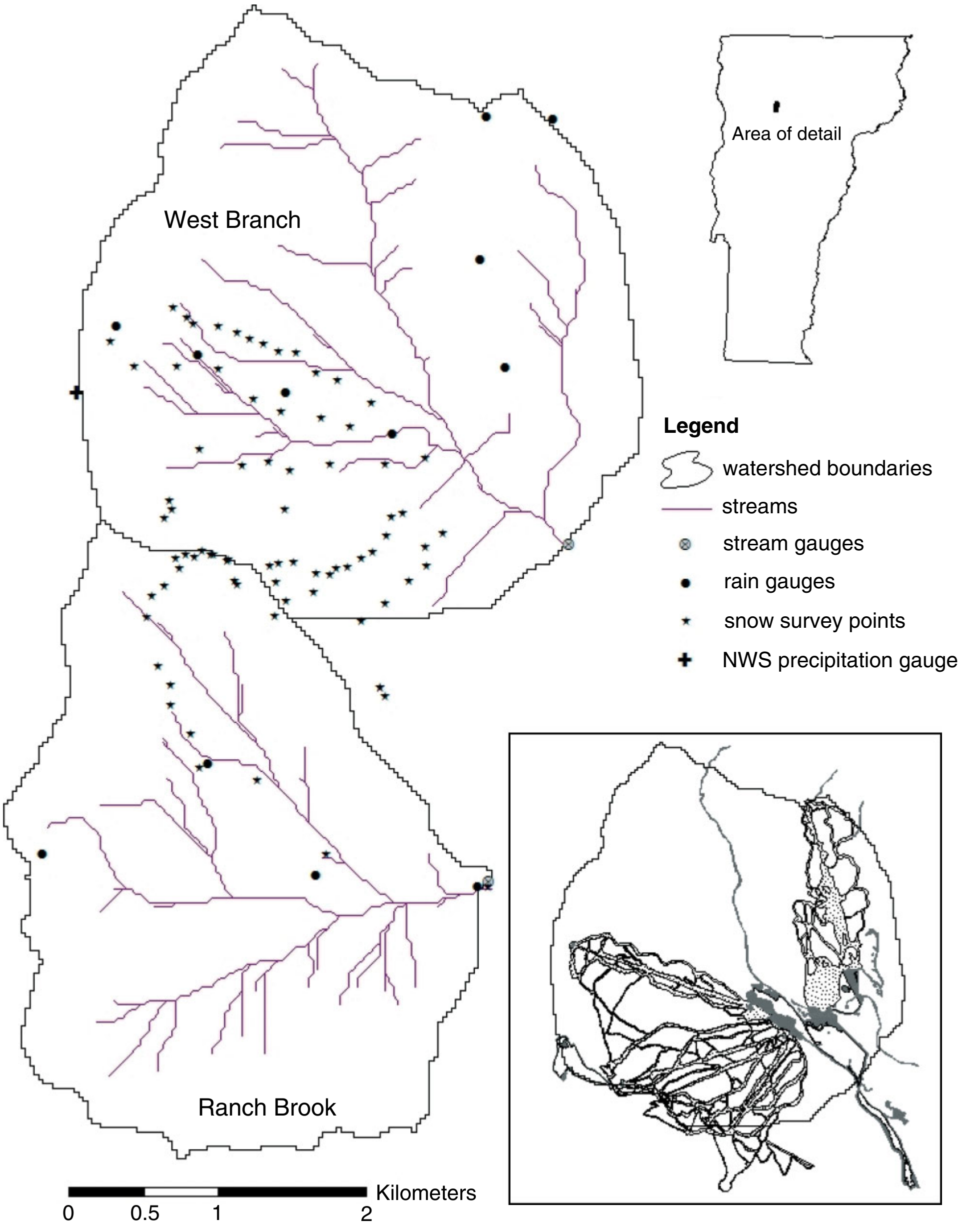

Figure 1. West Branch and Ranch Brook watersheds with locations of gauging and precipitation monitoring stations. USGS precipitation gauge is on the roof of the West Branch gauging station and not shown as a separate symbol on the map. The inset map shows the extent of development in ski trails (stippled pattern) and roads and parking lots (shaded grey) in the West Branch basin

with Rocky Mountain and European destinations. Expansion activities include the development of slope-side villages, expansion of trail networks, enhancing artificial snowmaking capacity to provide reliable snow cover and extend the ski season, and a diversification into four-season resorts through development of golf courses, water parks, and other non-winter sporting activities.

The body of scientific literature in the US on the effects of alpine ski area operations on watershed processes is sparse and drawn largely from a few studies conducted in the western states (Shanley and Wemple, 2002). A series of studies in the southern Rocky Mountains documented minimal impacts of ski area operations on bacteriological water quality, elevated levels of heavy metals, elevated levels of dissolved ions, and some impacts on the aquatic macroinvertebrate community (Gosz, 1977; Moore *et al.*, 1978; White *et al.*, 1978; Molles and Gosz, 1980). Studies in Colorado have estimated consumptive losses from man-made snowmaking that range from 13–37% of water used for snowmaking, but the authors caution that consumptive losses would be considerably less in more humid areas such as the eastern USA (Eisel *et al.*, 1988, 1990). Several studies have attempted to understand how compaction of snow by trail grooming at ski areas influences snowpack depth, snow water content, and melt rates at ski areas in the western US (Grady, 1982; Kattelmann, 1985) and in New England (Chase, 1984). Recent explorations are probing the implications of acid rock drainage on the growth potential of western US ski resorts (Todd *et al.*, 2003). We are aware of only one peer-reviewed scientific study aimed at evaluating the effects of ski area operations on watershed hydrology and water quality in the northeastern US This study is based on strip cutting at the Hubbard Brook Experimental Forest as an analog for ski trail development (Hornbeck and Stuart, 1976). The authors suggest that only modest changes in streamflow and water quality might occur from ski areas, though they acknowledge distinct differences between the strip cutting example and alpine ski area development.

At least four factors associated with ski area development may lead to effects on watershed processes that are distinct from those associated with traditional forest management practices. First, forest clearings created for ski trails are oriented along gravitational flow paths, enhancing the potential for efficient down slope routing of water, solutes and particulates. Second, forest clearings for ski trails are intended to persist over time and represent a relatively permanent alteration of the forest landscape. Third, certain activities associated with ski area development, particularly artificial snowmaking, are not present in traditional forest management operations. Finally, other practices, including creation of impervious surfaces and development of drainage infrastructure are more extensive than those associated with traditional forest management practices.

Here, we report findings for water years (WY) 2001–2003 of a study examining high elevation watershed processes in a region undergoing alpine resort development. Our study is designed as a paired watershed experiment, encompassing two adjacent watersheds on the eastern slope of Mt Mansfield, Vermont's highest peak. Our goals include documenting the hydrologic and biogeochemical behaviour of these high-elevation watersheds and the effects of current resort development. Our observations will also provide baseline data to examine future development in one of the watersheds and to validate hydrologic models of development effects.

Approach

Study area

The study area includes the West Branch (11·7 km^2) and Ranch Brook (9·6 km^2) watersheds on the eastern slope of Mt Mansfield, in north-central Vermont (Figure 1). The basins are adjacent and similar in size, shape, aspect and drainage patterns. Elevation ranges from 415 to 1340 m in the West Branch basin and from 335 to 1173 m in the Ranch Brook basin (Figure 2). The bedrock geology of both basins is quartz-muscovite-chlorite and gneiss of the Fayston and Hazens Notch formations (Christman, 1959; Thompson and Thompson, 1998). Roughly 87% of the West Branch basin falls within the Hazens Notch formation, which also includes a rusty weathered quartz-muscovite-chlorite-pyrite schist member. Soils are all Spodosols developed on glacial till, characterized as coarse-loamy to fine sandy loams, and moderately stony with rock fragments ranging from pebbles to cobbles and comprising 0–35% of the profile (Babcock, 1981; Allen, 1989). Soils are dominated by the Londonderry and Stratton series (20–40 cm depth to bedrock) at upper elevations, Tunbridge and Lyman series (40–50 cm depth to bedrock) at elevations roughly between 500 and 900 m, and the Marlow and Colton-Duxbury series (typically 150 cm depth to bedrock) at elevations below 600 m. These lower-elevation soils have a layer of dense basal till (Cd horizon) below a B horizon (typically near 70 cm). All soil units within the watersheds are characterized as well drained with moderate to moderately high permeability, although drainage in the basal till of the low-elevation soils is moderately slow. Full descriptions of each soil series are given by the Natural Resource Conservation Service (http://ortho.ftw.nrcs.usda.gov/cgi-bin/osd/osdnamequery.cgi).

Climate and vegetation within the study area is typical of the mixed northern hardwood coniferous forests of the region. On average, annual precipitation is relatively evenly distributed throughout the year. Snow at the highest elevations begins in late October to early November in most years, and a seasonal snowpack typically covers the entire basins beginning in December. Snowmelt typically occurs from mid-March through late May. The forest is comprised of northern hardwood species, including sugar maple (*Acer Saccharum*), beech (*Fagus grandifolia*), yellow birch (*Betula alleghaniensis*), red maple (*Acer rubrum*) and paper birch (*Betula papyrifera*), at elevations below 750 m, giving way to conifers, including red spruce (*Picea rubens*) and balsam fir (*Abies balsamea*), at higher elevations.

Ranch Brook is a relatively pristine, forested watershed and is managed by the Vermont Agency of Natural Resources for research purposes. It contains a network of cross country ski trails operated by a commercial centre. Approximately 1% of the basin is non-forested as trails, access roads, and exposed bedrock outcrops. The West Branch watershed encompasses an existing alpine ski resort, with approximately 17% of the basin occupied by trails, roads, impervious surfaces, and bedrock outcrops. The resort has received approval for an expansion

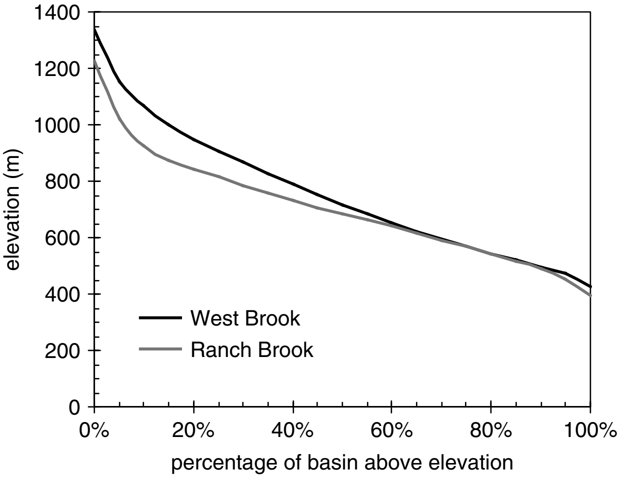

Figure 2. Basin hypsometric curves

that will include development of a base village (condominiums, shops and restaurants), mountainside vacation homes, new clearings for ski trails and a golf course, construction of a new water storage pond, and extension of snowmaking coverage to 100% of all ski trails. After the expansion, cleared and impervious areas will cover approximately 24% of the basin. Ground breaking for construction of the new base village began in the summer of 2003.

Field measurements and sampling

Our measurement program began in October 2000 with the installation of gauging stations for continuous monitoring of stream flow (Table I). At each site, stage is measured by a pressure transducer and recorded at 5 min intervals by a Campbell CR-10 datalogger. The Ranch Brook gauge utilizes natural channel control, whereas the West Branch gauge has a thin plate rectangular weir. When needed, water for snowmaking is diverted from the weir pool at West Branch to an adjacent snowmaking pond by opening a gate. Water diverted to the snowmaking pond does not flow through the weir and does not contribute to measured streamflow; hence, water recycled within the basin for artificial snowmaking is only measured when it ultimately flows out of the basin and past our gauging station. Stage-discharge relations at both gauges were determined empirically and are reevaluated annually. Descriptions of the stream gauging stations and published streamflow data are available through the US Geological Survey (USGS) (Coakley *et al.*, 2002).

Flow-activated water sampling using Teledyne ISCO automated samplers for analysis of suspended sediment concentration (SSC) and major dissolved solutes began in March 2001 at the gauging stations of both basins. The intake nozzle was a standard ISCO strainer, approximately 20 cm long with multiple holes. It was elevated approximately 0·3 m above the stream bed and approximately 1 m from a vertical retaining wall, oriented downstream, and located in a riffle where suspended sediment is generally thought to be well mixed in mountain streams (Thomas, 1985). Sampling occurred over a wide range of flow events, typically including up to 12 samples per storm event at each watershed, ensuring characterization of temporal variability in suspended sediment and solute concentrations.

Precipitation was monitored using two permanent installations and a distributed network of rain gauges and snow pack surveys that were operated for limited time periods (Figure 1, Table I). Permanent installations include a standard (20 cm diameter) shielded non-recording precipitation gauge at 1204 m, below the summit of Mt Mansfield near the divide between the West Branch and Ranch Brook watersheds and operated by the National Weather Service (NWS) since 1953, and a MetOne unshielded, heated tipping bucket rain gauge located at 430 m, at the West Branch gauging station and operated by the USGS since its installation in October 2002. During the summer and fall of 2002 and 2003, we installed and monitored a network of unshielded Hobo recording rain gauges along three elevational transects in the watersheds. In April 2004, we conducted snow surveys to measure snow depth and water equivalent at 77 points along seven elevational transects in the two basins. For each snow water equivalent (SWE) determination, five measurements were averaged. SWE was measured near peak accumulation before appreciable melt had occurred. Though some mid-winter rain or melt may have caused limited runoff, the SWE measurements should represent most of the winter precipitation.

Laboratory analysis

Water quality analyses were conducted using standard methods in laboratories at the University of Vermont.

Table I. Details of existing physical measurements and stream water quality sampling in the study basins

Measurement/Sampling	Measurement period	Frequency	Method
Streamflow	10/2000—present	Continuous (5 min)	Pressure transducer
Air temperature	10/2001—present	Continuous (5 min)	Thermister
Water temperature	10/2001—present	Continuous (5 min)	Thermister
Precipitation—low elevation (430 m)[a]	10/2001—present	Continuous (5 min) when raining	Tipping bucket (heated), unshielded
Precipitation—high elevation (1204 m)[b]	11/1953—present	Daily totals measured at 1800 EST	Standard, non-recording, shielded
Precipitation—distributed[c]	7/2002–9/2002 and 5/2003–10/2003	Continuous with rainfall	Tipping bucket, unshielded
Suspended sediment	3/2001—present	Periodic (stage activated and grab)	ISCO automated sampler
Cations (Ca, K, Mg, Na, Si)	3/2001—present	Periodic (stage activated and grab)	ISCO automated sampler
Anions (Cl, NO_3, SO_4)	3/2001—present	Periodic (stage activated and grab)	ISCO automated sampler

[a] Represents USGS precipitation gauge at West Branch gauging station.

[b] Represents NWS precipitation gauge near the summit of Mt Mansfield.

[c] Represents distributed precipitation network of 12 tipping bucket gauges arrayed in three transects to capture controls of elevation and aspect on precipitation. All other measurements are at gauging stations for each watershed. See Figure 1 for locations of measurement points.

Total suspended solids were measured on 1-L samples filtered on 1·5-μm fibreglass filters and oven dried overnight at 105 °C. The organic fraction was determined by loss on ignition at 550 °C for 30 min. Major anion concentrations were measured on a Dionex 600DX model ion chromatograph (Dionex Corp., Sunnyvale, CA) with an AS14A anion column. Major cation and silicon concentrations were measured on a Perkin-Elmer Optima 3000DV Inductively-Coupled Plasma Optical Emissions Spectrometer (Perkin-Elmer, Norwalk, CT).

Data analysis

Spatial patterns and elevation trends in precipitation distribution for the watersheds were assessed using measurements from the two permanent precipitation stations and our distributed precipitation monitoring network. Annual precipitation lapse rates were derived from the difference in precipitation depths recorded at the USGS and NWS stations in WY 2002 and 2003, when data from both sites were available. Trends in precipitation with elevation were assessed with linear regression models fit to data collected from our distributed network of Hobo rain gauges and the USGS and NWS stations for two periods: 1 month in summer, 2002 and 4 months in the summer and fall of 2003. Snow survey data were used to assess precipitation–elevation trends for the snow season spanning the period from 20, November 2003 (when a seasonal snowpack developed at 400 m) to 4, April 2004, when our survey was conducted.

Annual precipitation depths for each watershed were estimated from simple linear interpolation between the two continuously recording precipitation gauges of the USGS and NWS. The interpolation was accomplished by applying an annual precipitation lapse rate to the hypsometric curve of each watershed to determine an annual areally averaged precipitation depth. The annual lapse rate for WY 2002 and WY2003 was derived from the difference in annual precipitation totals at the two stations. For WY 2001, when precipitation was not measured at the USGS station, an average of the WY2002 and WY2003 lapse rate was used (Table II).

Artificial snowmaking water consumption was taken from values reported to the Vermont Agency of Natural Resources (ANR) by the resort operating in the West Branch watershed (unpublished data provided by J. Cueto, Hydrologist, Vermont ANR). Snowmaking water use is reported as a volume of water applied to the slopes from the snowmaking pond and was divided by area of the West Branch watershed and given as a depth in Table III.

Table II. Annual precipitation totals (mm) and precipitation lapse rates (mm m^{-1} $year^{-1}$) used in estimates of basin total precipitation depth. See Figure 1 for station locations

	Station (elevation)		
	USGS (430 m)	NWS (1204 m)	Lapse rate
WY 2001	—	1853	0.893[a]
WY 2002	1395	2018	0.805
WY 2003	1053	1812	0.981

[a] Precipitation depth not available for USGS station in WY2001. Lapse rate used in calculations is average of WY 2002 and WY2003 values.

Runoff metrics were determined from continuous hydrograph records. Annual water yield was summed from hourly discharge values and normalized to basin area. Spring runoff (‘snowmelt’) was determined in each basin by summing the discharge over the period from 15 March to 31 May. Runoff during this period is dominated by snowmelt, but also includes baseflow and rain-on-snow events.

Empirical equations were used to establish the relationship between streamflow and both solute and sediment concentrations in order to estimate annual fluxes (Table IV). Concentration–discharge relationships for dissolved solutes took the general form

$$Y = b_0 + b_1 Q_J + b_2 \sin\tau + b_3 \cos\tau \tag{1}$$

where Y is solute concentration, τ is a time term equal to ($2 \times \pi \times$ day of year/365), Q_J is a transformation of the discharge (Q) of the form

$$Q_J = 1/(1 + \beta\, Q) \tag{2}$$

(after Johnson *et al.*, 1969), the b_i terms are regression coefficients, and the parameter β is estimated through optimization of the regression model given in (1). Use of the sine and cosine terms incorporates seasonal fluctuations in solute concentrations (Aulenbach and Hooper, 2006). The rating curves for total suspended solids took the form

$$\ln Y = b_0 + b_1 \ln Q + b_2\, season + b_3\, I_{SQ} + b_3\, rising + b_3\, I_{SR} \tag{3}$$

where lnY is the natural logarithm of the concentration suspended solids, lnQ is the natural logarithm of discharge (cfs); *season* is a binary variable set to 0 for the period from 1, December to 31, May and 1 otherwise; *rising* is a binary variable set to 1 on the rising limb of the hydrograph up to 2 h before the hydrograph peak, and 0 otherwise, I_{SQ} is an interaction term between season and discharge ($season \times \ln Q$) and I_{SR} is an interaction term between season and rising limb ($season \times rising$). Regression models were based on the 3 years of samples for solutes but only on samples collected during WY 2001 and WY 2002 for total suspended solids, to eliminate samples collected during late summer 2003 after construction activity began and substantial ground disturbance near the West Branch gauging station occurred. Annual suspended sediment and solute yields were computed from the continuous hydrograph record using regression-derived concentrations multiplied by the average hourly discharge and summed for the water year. Uncertainty ranges in annual load estimates were assessed using 95% confidence bounds for predictions of average

Table III. Estimates of water balance terms for the Ranch Brook and West Branch watersheds, water years 2001–2003

	Ranch Brook			West Branch		
	WY 01	WY 02	WY 03	WY 01	WY 02	WY 03
Precipitation depth (mm)	1404	1613	1318	1449	1653	1368
Runoff depth (mm)	872	1173	958	1190	1416	1132
Runoff/precip ratio	0.62	0.73	0.73	0.82	0.86	0.83
Precip-runoff (mm)	532	440	360	259	237	236
Snowmaking depth (mm)				47	45	53
Snowmaking/natural precip				0.03	0.03	0.04
Snowmelt depth (mm)	442	554	458	569	699	575
Fraction of runoff as snowmelt	0.51	0.47	0.48	0.50	0.49	0.51

Table IV. Regression models for solutes and suspended load concentrations. See text for definition of regression terms

Variable (units)		Regression coefficients (and standard errors)							Adj
	WS[a]	Constant	Q_J	sin τ	cos τ			β[b]	R[b]
Na (mg/L)	RB	0·56 (0·02)[c]						—	—
	WB	−0·51 (0·42)	17·24 (0·94)	3·89 (0·26)	3·20 (0·53)			0·075	0·63
Ca (mg/L)	RB	1·73 (0·04)	1·63 (0·09)	0·05 (0·02)	0·37 (0·05)			0·13	0·58
	WB	2·29 (0·01)	6·04 (0·22)	0·58 (0·06)	0·55 (0·13)			0·075	0·73
Mg (mg/L)	RB	0·33 (0·01)	0·35 (0·02)	0·02 (0·01)	0·10 (0·01)			0·155	0·53
	WB	0·37 (0·02)	0·84 (0·03)	0·09 (0·01)	0·11 (0·02)			0·055	0·71
K (mg/L)	RB	0·46 (0·06)[c]						—	—
	WB	0·51 (0·01)[c]						—	—
Si (mg/L)	RB	0·96 (0·04)	1·20 (0·10)	−0·07 (0·03)	0·02 (0·05)			0·14	0·40
	WB	0·94 (0·03)	1·17 (0·06)	−0·08 (0·02)	0·16 (0·03)			0·065	0·66
NO_3 (mg/L)	RB	0·41 (0·02)	1·17 (0·42)	0·31 (0·02)	0·26 (0·03)			5·01	0·63
	WB	0·52 (0·01)	−0·01 (0·002)	0·29 (0·01)	0·19 (0·03)			0·275	0·67
SO_4 (mg/L)	RB	1·12 (0·02)	0·67 (0·04)	−0·09 (0·01)	0·17 (0·02)			0·12	0·71
	WB	1·42 (0·03)	1·08 (0·06)	−0·08 (0·02)	0·17 (0·04)			0·055	0·58
Cl (mg/L)	RB	0·40 (0·02)[c]						—	—
	WB	−3·85 (0·74)	29·67 (1·47)	7·00 (0·44)	6·08 (0·93)			0·05	0·61
		Constant	lnQ	Season	I_{SQ}	Rising	I_{SR}		
SSC (mg/L)	RB	−2·25 (0·43)	1·03 (0·11)	3·31 (0·54)	−1·03 (0·15)	0·01 (0·26)	0·92 (0·37)	—	0·36
	WB	−1·32 (0·42)	0·82 (0·11)	3·85 (0·60)	−1·07 (0·15)	1·08 (0·28)	0·86 (0·40)	—	0·40

[a] Watershed: RB, Ranch Brook; WB, West Branch.
[b] Transformation parameter for flow variable $Q_J = 1/(1 + \beta Q)$ (Q in cfs).
[c] Denotes average concentration values used for variables with no significant relationship to discharge or season.

solute or sediment concentration at each hourly discharge value over the 3-year period of record, multiplied by the average hourly discharge, and summed for the water year. Annual solute inputs in precipitation and dry deposition were estimated using the regional model of Ollinger *et al.* (1993).

Results

Hydrology

Precipitation is relatively evenly distributed through the year in our study area and increases substantially with elevation (Figure 3). Monthly precipitation averaged 102 mm for the 2 years monitored during our study at the USGS gauge at 430 m, and 160 mm for the 3 years of our study at the NWS gauge at 1204 m, a difference of roughly 0·075 mm m^{-1} month^{-1} or 0·899 mm m^{-1} year^{-1}. These trends vary slightly on a year-to-year basis with precipitation increasing 0·804 mm m^{-1} year^{-1} in WY2002 and 0·9815 mm m^{-1} year^{-1} in WY2003 (Table II). Winter precipitation recorded at the NWS station between 1, December and 30, April the period when snowfall typically occurs, totaled 46% of annual precipitation at this station in WY01 and 36% of annual precipitation in WY02 and WY03

Our distributed precipitation measurements show similar trends in increasing precipitation with elevation and suggest some differences between basins in winter precipitation patterns. Rainfall increased 0·0024 mm m^{-1} day^{-1} (0·876 mm m^{-1} year^{-1}) for a 30-day period in fall, 2002 and 0·0018 mm m^{-1} day^{-1} (0·675 mm m^{-1} year^{-1}) for a 4-month period in summer/fall of 2003 (Figure 4). During these two monitoring periods, no differences between basins were apparent in the rainfall depths. In contrast, snowpack measurements recording 4·5 months of snow accumulation in the winter of 2003–2004 indicate significant differences between basins in the relationship between precipitation and

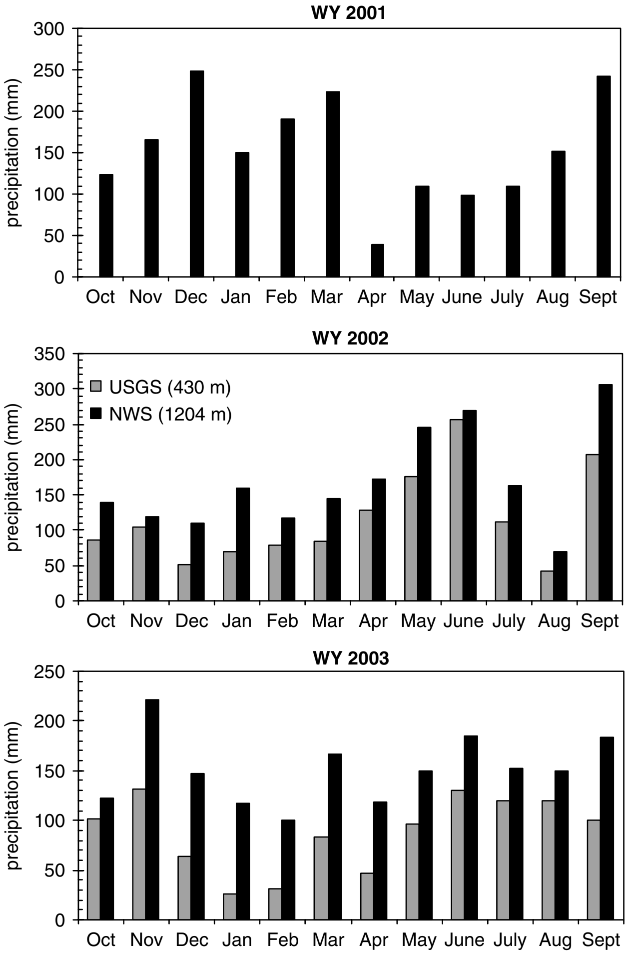

Figure 3. Monthly precipitation totals measured at the USGS and NWS precipitation gauges for water years 2001–2003. Note, precipitation was not measured at the USGS gauge in WY 2001

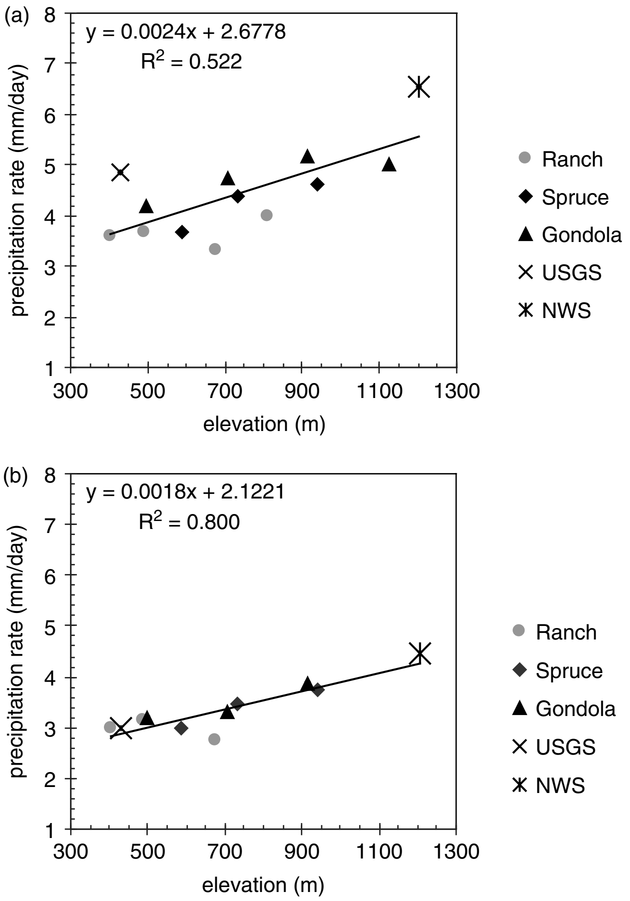

Figure 4. Measurements and trend lines from distributed precipitation monitoring (a) 18 September–17 October 2002 and (b) 16 June–14 October 2003. See Figure 1 for locations of rain gauges

elevation, although the magnitude of these lapse rates is probably overestimated, since they were made after some melt had occurred at lower elevations (Figure 5).

Areally averaged estimates of annual precipitation over the three-year study period ranged from 1368–1653 mm in West Branch and from 1318–1613 mm in Ranch Brook (Table III). The slightly higher estimates at West Branch are due to its higher elevation distribution (Figure 2). Artificial snowmaking represents a small fraction of the annual water balance at only 3–4% of the natural precipitation in this basin (Table III).

Runoff for the 3-year period ranged from 1132 to 1416 mm in West Branch and from 872 to 1173 mm in Ranch Brook (Table III). The difference in annual runoff between the basins ranged from 174 to 318 mm and was most pronounced in WY 2001 when water yield from West Branch was 36% greater than from Ranch Brook. In WY 2002 and WY 2003, water yield from West Branch was roughly 20% greater than from Ranch Brook. Snowmelt is an important component of annual runoff, representing roughly 50% of total annual runoff in each basin for all three water years.

The difference between precipitation (P) and runoff (Q) differed considerably for the two basins (Table III). P–Q averaged 444 mm in Ranch Brook

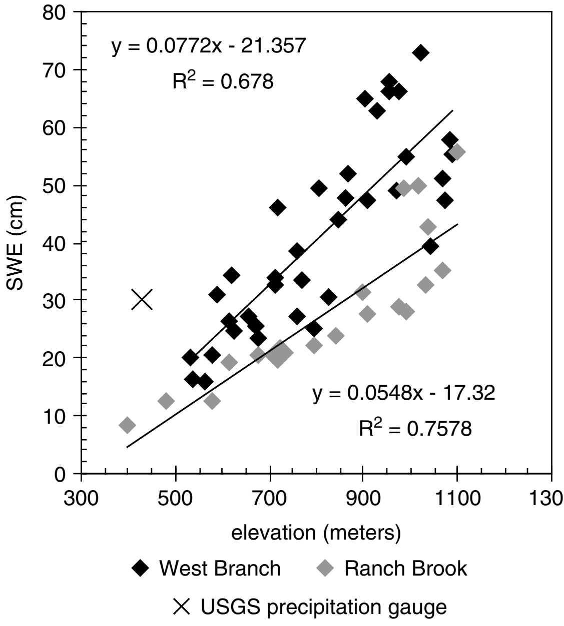

Figure 5. Snow water equivalent (cm) as a function of elevation for snow cores sampled on 4 April 2004 and trend lines for West Branch and Ranch Brook measurements. Slopes of the trend lines are significantly different ($p < 0.05$). Note that winter precipitation measured by the heated tipping bucket at West Branch gauge exceeded SWE at this elevation on 4 April 2004, indicating prior snowmelt or rain-on-snow at lower elevations

and 244 mm in West Branch, a difference of 200 mm/year, but year-to-year differences in P–Q between the two basins varied considerably, ranging from 273 mm in WY01 to only 124 mm in WY03.

Suspended sediment

Suspended sediment concentrations during spring snowmelt and summer/fall storms displayed seasonal and inter-basin differences (Figure 6). Sediment concentrations remained relatively low in both watersheds during the spring snowmelt period and were relatively insensitive to changes in discharge, a result that is likely due to the ground surface protection provided by snow cover. During storms in summer and fall, sediment concentrations increased in both watersheds on the rising limb of storm hydrographs, peaking in advance of the runoff peak, a pattern common in streams with limited sediment supply. Despite this common pattern during rainfall events, sediment concentrations were consistently higher in West Branch than in Ranch Brook throughout the 3-year study period (Figure 7). During the summer of 2003, after construction began in West Branch, sediment concentrations reached higher levels than noted in the previous 2 years. Estimated suspended sediment yields averaged 163 kg/ha/year in West Branch and 61 kg/ha/year in Ranch Brook over the 3-year study period (Figure 8). Uncertainty in these estimates is great, however, owing to the wide variation in sediment concentrations over sampled discharges and the marginal explanatory power of the regression model used to relate sediment concentration to discharge (Figure 8; Table IV).

Major solute chemistry

In both basins, all major solutes except nitrate varied inversely with stream discharge. Nitrate generally increased with increasing flow. Solute concentrations were more strongly linked to stream discharge at West Branch than at Ranch Brook, as evidenced by the generally higher percent variance explained by the regression models (Table IV). Where significant, regression models explained roughly 60–70% of the variance in solute concentrations, and thus provided an excellent basis for the solute flux calculations. The regression models were dominated by the discharge term, but also contained a seasonal component that generally accounted for about 10% of the variance. For Na and Cl, highly significant models were developed for West Branch while none was possible for Ranch Brook. Neither basin yielded a significant model for K (Table IV).

Input fluxes in precipitation, as estimated from the Ollinger *et al.* (1993) regional model, were similar for the two basins. The model estimates average annual solute concentrations in precipitation based on latitude and longitude, and assumes concentration does not vary with elevation. West Branch thus had slightly higher inputs of all solutes because of its higher precipitation. Inputs were generally small relative to streamwater outputs, except for sulfate and nitrate, for which inputs and outputs were similar in magnitude (Figure 8).

Output fluxes in streamwater were higher for all solutes in all three water years at West Branch compared to Ranch Brook, by factors generally ranging from 1·2 to 2·5 (Figure 8). However, fluxes of Na and Ca were about an order of magnitude greater at West Branch as a result of deicing salt applications in the West Branch basin. Despite the seasonal (winter) application of deicing salts, elevated Cl concentrations persisted throughout the year in West Branch stream water (Figure 6). The excess solute flux at West Branch relative to Ranch Brook was more than could be explained by the greater water flux at West Branch, except for Si, where the differential was about equal to that of water. Uncertainty in the estimates of annual solute yields was greatest for Na and Cl in West Branch and quite small for all other solutes in both watersheds (Figure 8).

Discussion

Hydrological and chemical patterns in the control watershed correspond well to observations from other studies in the northeastern US, indicating that these basins represent an excellent setting for the study of high-elevation

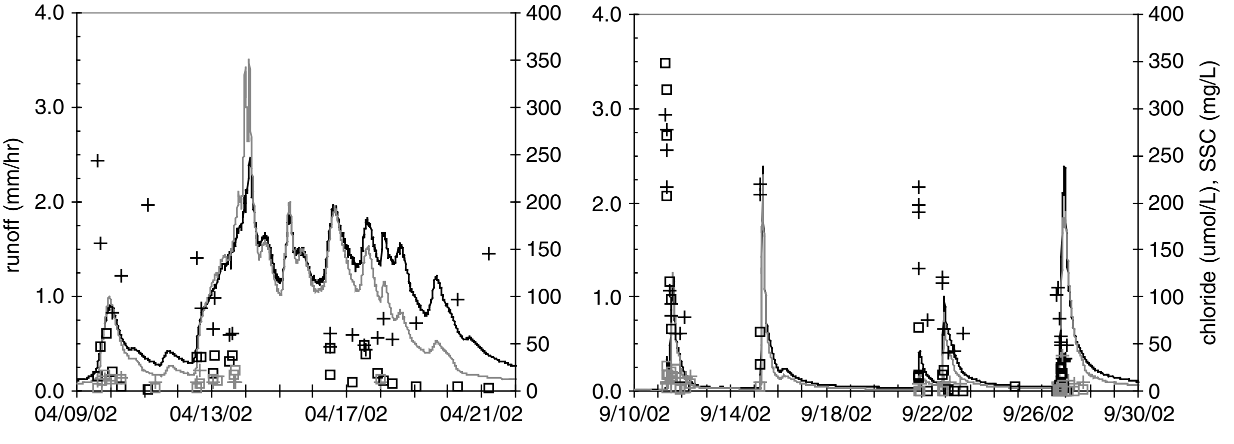

Figure 6. Hydrographs (lines) and concentrations of suspended sediment (boxes) and chloride (crosses) in the Ranch Brook (grey lines and symbols) and West Branch (black lines and symbols) basins during spring snowmelt and summer storms in 2003

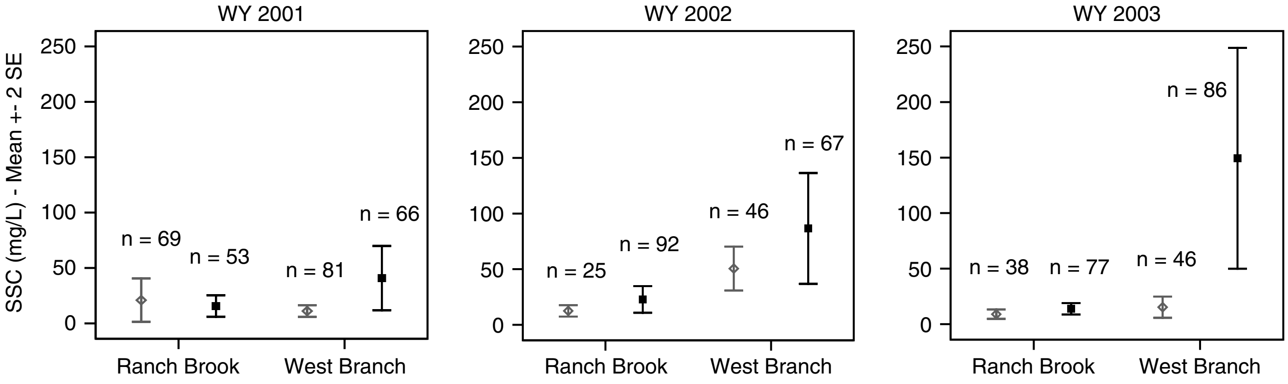

Figure 7. Mean (±2 standard errors) concentration of suspended sediment for samples collected during spring snowmelt (grey bars) and summer/fall storms (black bars) for water years 2001–2003. Note, samples are not collected between late November and early March when streams are frozen

development for generalization to the region. Precipitation lapse rates noted here agree closely with those documented by Dingman (1981) and Ollinger *et al.* (1995) for the region. The difference between precipitation and runoff (P–Q) in Ranch Brook falls within the range noted by Dingman (1981) for other New England watersheds, and the average value of P–Q in Ranch Brook, 444 mm/year, is comparable to estimates of evapotranspiration at the Hubbard Brook Experimental Forest in New Hampshire (Likens and Bormann, 1995). Annual water yield in Ranch Brook is at the upper range of observed values in the eastern US (Sopper and Lull, 1965) but not beyond what might be expected for basins at this elevation (Dingman, 1981). The fluxes of all solutes in Ranch Brook are comparable to those reported at Hubbard Brook (Likens and Bormann, 1995). These findings suggest that these basins are generally representative of base-poor sites in the northeastern US and that results noted here may be extended to similar environments throughout the region.

Solute fluxes in stream water (Figure 8) generally reflect the regionally elevated levels of nitrate and sulfate in atmospheric deposition and the fairly low base cation fluxes expected from low weathering rates of the unreactive gneiss bedrock, highlighting certain regional behaviours. Streamwater outputs of cations at Ranch Brook were about an order of magnitude greater than precipitation inputs, except only a 3- to 4-fold increase for Na. Nitrate export is somewhat less than the total estimated N deposition (wet plus dry), suggesting some watershed retention of nitrogen, although dissolved organic nitrogen is an additional output that was not measured. Some N retention would be expected in an aging second growth forest (Aber *et al.*, 1998). The somewhat greater nitrate fluxes at West Branch could potentially be a result of nitrate loading from septage or other anthropogenic sources, and/or from net mineralization due to land disturbance on the mountain. Sulfate export is in approximate balance with estimated S inputs at Ranch Brook, as is typical for northeastern USA watersheds (Rochelle *et al.*, 1987; Likens and Bormann, 1995). The greater export of sulfate at West Branch is most likely caused by the weathering of sulfides in the Hazens Notch Formation which underlies most of that basin.

Some patterns in water quality dynamics noted here are consistent with differences in land use in the two basins and suggest some detectable water quality effects of the existing ski area. Annual sediment yield in the developed basin exceeded that in the control basin by a factor greater than 2·5, and output fluxes of all solutes in the developed basin exceeded those in the control basin, owing either to greater water fluxes or contamination of streamwater by deicing salts. Higher concentrations of suspended sediment and chloride at West Branch reflect the contributions of road surfaces and parking lots that receive high traffic levels and are located close to streams. The contribution of suspended sediment from developed surfaces was evidenced by marked increases in suspended sediment concentrations in water samples collected after ground breaking on new development in the summer of 2003. Na and Cl fluxes were an order of magnitude greater at West Branch from deicing salts, but the molar Na/Cl ratio at West Branch was less than 1·0, indicating that some of the added Na exchanged for Ca and Mg on soil exchange sites (Shanley, 1994). This mechanism may explain the differentially greater export of Ca and Mg at West Branch relative to Si and K. The greater flux of the latter two solutes is in proportion to the greater water flux.

Differences in annual water yield between the two basins ranged from 18 to 36% and were greater than we expected based on regional studies of forest treatment effects on water yield (Hornbeck *et al.*, 1993). Three possible explanations exist for the greater-than-expected differences in runoff in West Branch relative to Ranch Brook: (1) less groundwater loss or extra-basin groundwater inputs; (2) greater precipitation capture; or (3) less evapotranspiration and lower recharge due to forest removal and runoff over impervious surfaces. Dingman (1981) speculated that groundwater loss may be common in high-elevation watersheds, based on a regional water balance analysis. It seems unlikely that groundwater losses at Ranch Brook explain differences in water yield, since water yield at this site is already at the upper margin of annual runoff in the region at this elevation. It is

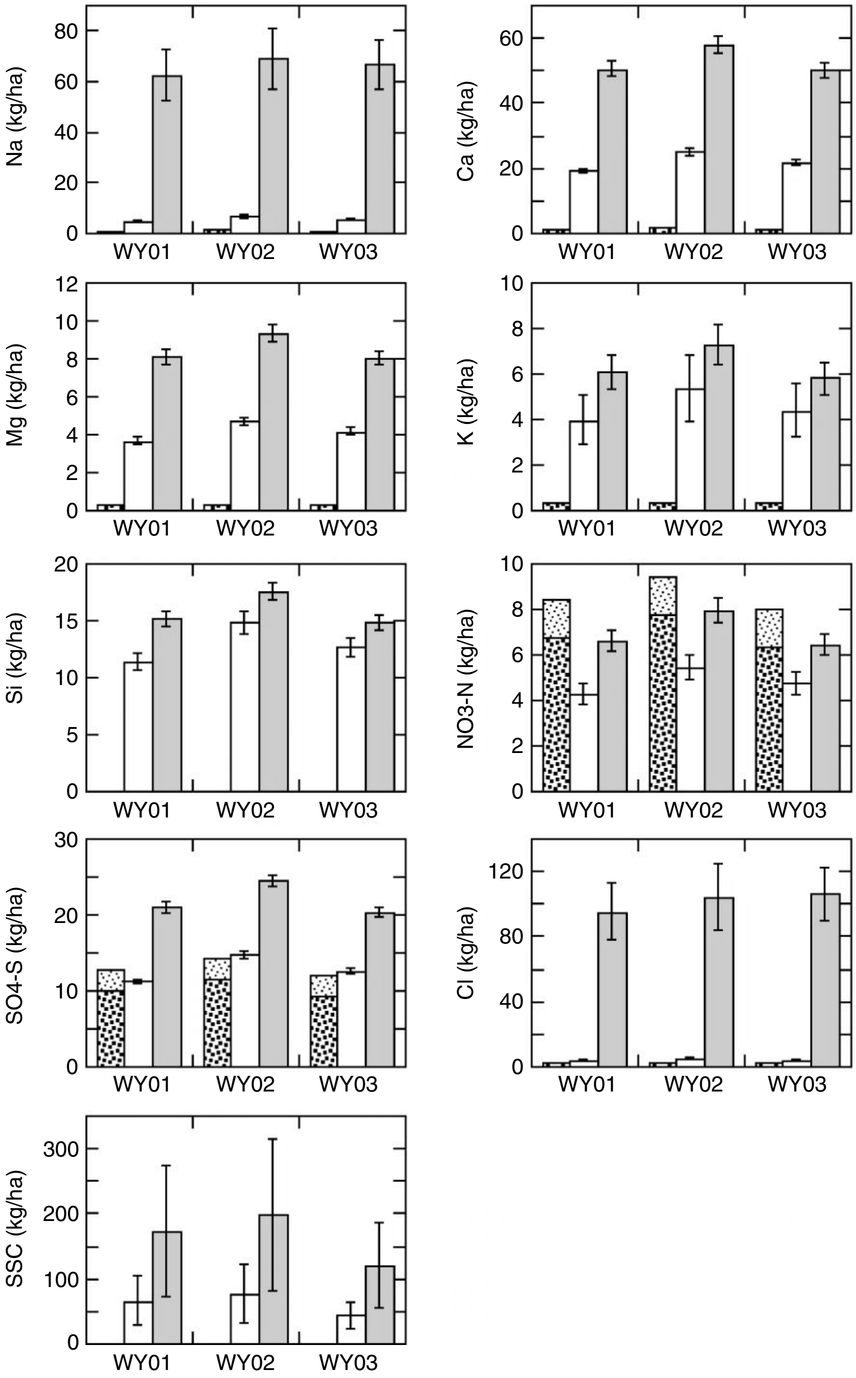

Figure 8. Annual estimated precipitation inputs (dotted bars) and calculated streamwater outputs for Ranch Brook (white bars) and West Branch (grey bars) for solutes and suspended sediment. Wet and dry deposition inputs are estimated as described in Ollinger *et al*. (1993). For nitrate and sulfate inputs, wet (heavy dots) and dry (light dots) depositions are shown. Inputs were computed separately for each basin but are presented in a single bar representing basin averages because differences were relatively minor. Error bars on streamwater outputs are uncertainty ranges for annual estimates based on 95% confidence intervals of hourly concentration predictions from regression models (see text for explanation)

possible, though, that West Branch captures groundwater from outside the surface watershed boundaries. Recent field studies indicate that streamflow in West Branch has a chemical signature that more closely matches deep groundwater than in Ranch Brook (Zinni, 2006), but we do not have sufficient data to determine whether any of this water originates from outside the basin. Another possible explanation for the differential water yield is error in our precipitation estimates. Our estimate of basin-average precipitation does not incorporate the known influences of other factors including slope, aspect, radiation, wind and vegetation (Wooldridge *et al*., 1996; Elder *et al*., 1998, Winstral *et al*., 2002) since we lack these data at our study sites, and does not incorporate more sophisticated estimation approaches (Dingman *et al*., 1988; Daly *et al*., 1994; Erxleben *et al*., 2002) that have been applied at sites with denser networks of meteorological stations and measured variables. We cannot quantify the uncertainty in our precipitation estimates and we have not incorporated seasonal differences in precipitation variability. The snow survey data for 2004 indicate that snow water equivalent was significantly greater in West Branch than in Ranch Brook (Figure 5). The higher water yield from the West Branch watershed may be due, in part, to greater precipitation input to this basin. This seems a likely scenario but one that requires expanded precipitation monitoring to verify. Finally, the spatial configuration of clearing and development in West Branch may enhance differences in water yield relative to Ranch Brook. Hornbeck *et al*. (1993) note that optimal configuration of clearings, particularly when clearings are made in large blocks near the watershed outlet, appears to have the effect of enhancing water yield for a given area cut. At West Branch, the configuration of clearings, including trails that are oriented along slope gradients and impervious areas situated near the watershed outlet, probably interact to efficiently convert precipitation to runoff.

This study lacks the control of a traditional paired-watershed study, in that there was no pre-development monitoring period; hence we cannot, with confidence, attribute all differences noted here to existing forest clearing and ski resort development. Differences in basin hypsometry, precipitation capture or groundwater fluxes may explain some of the difference in water yield. Elevated yield of sulfate in West Branch can be attributed to pyrite in the bedrock within this basin. Other subtle differences in watershed conditions can be expected, as reflected in regional comparisons of forested watersheds (Sopper and Lull, 1965). We can, however, see clear differences in some aspects of water quality that are consistent with the current land use conditions in the West Branch basin.

The results of this study are important in at least three respects. First, there exist few high-elevation hydrologic observatories for studying watershed processes in north-eastern US, despite the recognised importance of elevation in determining hydrologic behaviour in the region (Dingman, 1981). In fact, previous analyses in the region noted that only four long-term stream gauging stations located at mean basin elevations at or above 700 meters exist in Vermont and New Hampshire (Dingman, 1981; Olson, 2002). This study provides an important baseline dataset for high-elevation hydrologic processes. Second, there is little scientific literature specifically addressing the effects of recreational or resort development in mountain settings, particularly in eastern North America. Our results provide insight into how alpine ski resort development affects hydrology and water quality and could be used as a basis for understanding the effects of sub-urban development in the mountain landscape, a trend that is increasingly common in this and other regions (Stein *et al*., 2005). Finally, models and analytical methods applied to evaluating development effects are often unsuitable for the mountain setting in that they lack algorithms to treat snow pack accumulation and ablation, obscure a range of hydrologic processes through empirical approaches to rainfall/runoff relationships, and are largely unvalidated against observed conditions (due to the lack of a high-elevation monitoring network). This study provides a baseline dataset for model development and validation for future research and management decision making in high-elevation landscapes.

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