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RESEARCH AND OBSERVATORY CATCHMENTS: THE LEGACY AND THE FUTURE

WILEY

Hydrology on high: Assessing the effect of ski resort expansion and changing climate at the Mount Mansfield paired-catchment study in Vermont, USA

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Abstract

A paired-catchment study began in 2000 to assess the hydrologic effects of high-elevation development on Mt. Mansfield, Vermont's highest summit (1340 m). West Branch Little River drains 12.08 km^2 and encompasses a large ski resort. Adjacent Ranch Brook drains 9.83 km^2 of minimally disturbed second-growth forest. The two catchments have similar elevation, aspect, surficial and bedrock geology, and vegetation. The resort was well established before this study, but it underwent a major expansion during the period 2004–2008. The expansion included new ski lifts and trails, a large hotel, roads and second home development, a 435 000-m^3 snowmaking storage pond and a nine-hole golf course, increasing the extent of cleared/open land from 17% to 24%. Runoff from the developed West Branch Little River catchment was 21% greater than Ranch Brook over the duration of the study, but varied widely each year from 10% to 42%. This high variability occurs both on the interannual and individual storm scales, and is consistent with expectations from future climate projections. Hydrologic variability is on the rise, as shown by an increase in stream flashiness in both catchments over the 20 years of our study. Resort expansion, which provided for stormwater management, had no discernible effect on the overall runoff difference nor the flow distribution at the scale of the catchments, but sedimentation, water quality impacts and localized erosion cannot be ruled out. Forest clearing, impervious and hardened surfaces, and skier-compacted and machine-made snow may all cause enhanced runoff. However, the greater runoff at West Branch, which occurs primarily during snowmelt and summer, may arise partly from greater precipitation capture in the complex mountain topography. Development pressure on the mountain landscape continues to mount, but managers may also need to consider the confounding effects of a changing climate.

KEYWORDS
climate change, mountain development, runoff, ski resort, snowmaking, snowmelt

1 | INTRODUCTION

Mountain landscapes face increasing environmental pressure from recreational users, four-season resort and vacation home development, the energy sector—ridgeline wind turbines and solar farms—and the forest products industry. The high-elevation regions of the northeastern USA lie within easy reach of large population centres, and millions of people visit each year to hike, ski, mountain bike, view fall foliage and enjoy the amenities of mountain resorts. Due to greater precipitation and thinner soils with lower buffering capacity, high elevations have borne the brunt of anthropogenic pollution such as acid rain (Driscoll et al., 2001; Johnson & Siccama, 1983; Likens et al., 2021) and mercury deposition (Lawson et al., 2003; Rimmer et al., 2019), and intensified precipitation and climate warming (Dupigny-Giroux et al., 2018; Guilbert et al., 2014). An analysis by Nogués-Bravo et al. (2007) indicated that 21st-century climatic warming will be accelerated at higher elevations, particularly in high-latitude northern mountains. Reduced snowfall and shorter duration snowpacks under a warming climate cause earlier and reduced runoff (Rheinheimer et al., 2014; Tennant et al., 2015) and these changes pose a threat to the entire ski industry by the end of this century (Lazar et al., 2006; Scott et al., 2003).

Mountain catchments are particularly vulnerable to environmental change. Resistant bedrock such as granite and quartzite renders mountain areas sensitive to acid deposition (Likens et al., 2021; this issue), while thin soils and steep slopes leave them susceptible to erosion when forests are cleared (de Jong et al., 2015; Freppaz et al., 2013). Mountain resort and associated residential development may impact stream hydrology. For example, modelling by de Jong and Barth (2008) predicted a doubling of flow peaks in small streams due to an increase in impervious surfaces related to development at a ski resort in the French Alps. Water withdrawals for snowmaking may decrease baseflows if they are intra-basin or increase overall runoff if they are extra-basin. The higher peaks and added runoff can impair water quality not only from erosion, but also from flushing of septage and other pollutants. As a result of these characteristics, careful management of these vulnerable mountain environments is essential to mitigate effects of development and climate change.

The regulated community, state regulators and environmental agencies, non-profit groups, environmental consultants and academic and government scientists agree that additional scientific information would improve decision making when it comes to developing and managing our high-elevation landscapes. Many of the concerns over mountain landscapes centre in some way around water—too much, too little, quality degradation, water supply and wastewater disposal (Beniston & Stoffel, 2014; Viviroli et al., 2011). But the infrastructure to monitor water quantity and quality and determine development siting criteria is concentrated in the lowlands where most people live, leaving an information void at high elevations, where hydrologic monitoring and assessment is lacking (Viviroli et al., 2011).

Despite concerns, few studies directly assess the hydrologic effects of ski resorts. Aside from a short-term study in Sölden, Austria (Thonon, 2006), to our knowledge our earlier paper (Wemple et al., 2007) is the only paired-catchment study to directly assess runoff and water quality impacts of a ski resort. The East River watershed study in Colorado encompasses a ski resort within one of its gaged catchments but resort impacts are not a focus of the work (Kakalia et al., 2021; this issue). Lemonds and McCray (2007) modelled hydrology of a much larger stream draining several ski areas in Summit County, Colorado. Studies have addressed aspects of ski area hydrology and water quality impacts, notably in the western USA, as summarized in Shanley and Wemple (2009). In Colorado, where evaporative loss is a critical problem, Eisel et al. (1988, 1990) estimated that consumptive water losses from snowmaking may range from 13% to 37%. Other authors have studied the hydrologic implications of snow compaction on ski trails (Chase, 1984; Grady, 1982; Kattelmann, 1985). Hornbeck and Stuart (1976) evaluated the hydrologic effect of a partial strip cut as a proxy for ski trail clearing, and concluded that only modest changes in streamflow might occur. However, ski trails are oriented vertically and shed drainage waters laterally by design, such that this runoff may quickly find a connection to the stream network.

To address the lack of scientific information about the impacts of mountain development on hydrology and water quality, we established two streamflow monitoring stations draining streams of the eastern slopes of Mt. Mansfield, Vermont's iconic tallest mountain, two decades ago. Our scientific objective was to establish a baseline to assess changes associated with mountain resort development and a shifting climate. We hypothesized that impervious and compacted surfaces associated with ski resort expansion would enhance runoff at the expense of recharge in that watershed. Our work supplements and contextualizes ongoing monitoring of water chemistry, water temperature and aquatic biota by the state environmental regulatory agency, and serves as the longest, continuous record of high-elevation hydrology in the state. Earlier we described watershed chemical and sediment fluxes prior to the resort expansion project (Wemple et al., 2007), and subsequent work describes soil nitrification dynamics (Ross & Wemple, 2011) and nitrate fluxes in the undisturbed reference catchment (Ross et al., 2011). Here, we present hydrological findings on two decades of changing catchment hydrology in response to regional warming, extreme events and expanded development in this setting.

2 | SITE DESCRIPTION

The U.S. Geological Survey (USGS) gages on Ranch Brook (04288230) and West Branch Little River (West Branch; 04288225) near Stowe, Vermont were established in September 2000 as a paired-catchment study to assess effects of mountain development (Wemple et al., 2007; Figure 1 and Figure S1). Ranch Brook, the control catchment, is a 9.83-km^2 catchment that is 99% forested with only a small amount of land above treeline, a network of unpaved recreational trails, and a 0.1-km section of the paved mountain toll road within its area. As part of the Mt. Mansfield State Forest, Ranch Brook is managed by the Vermont Agency of Natural Resources. The West Branch

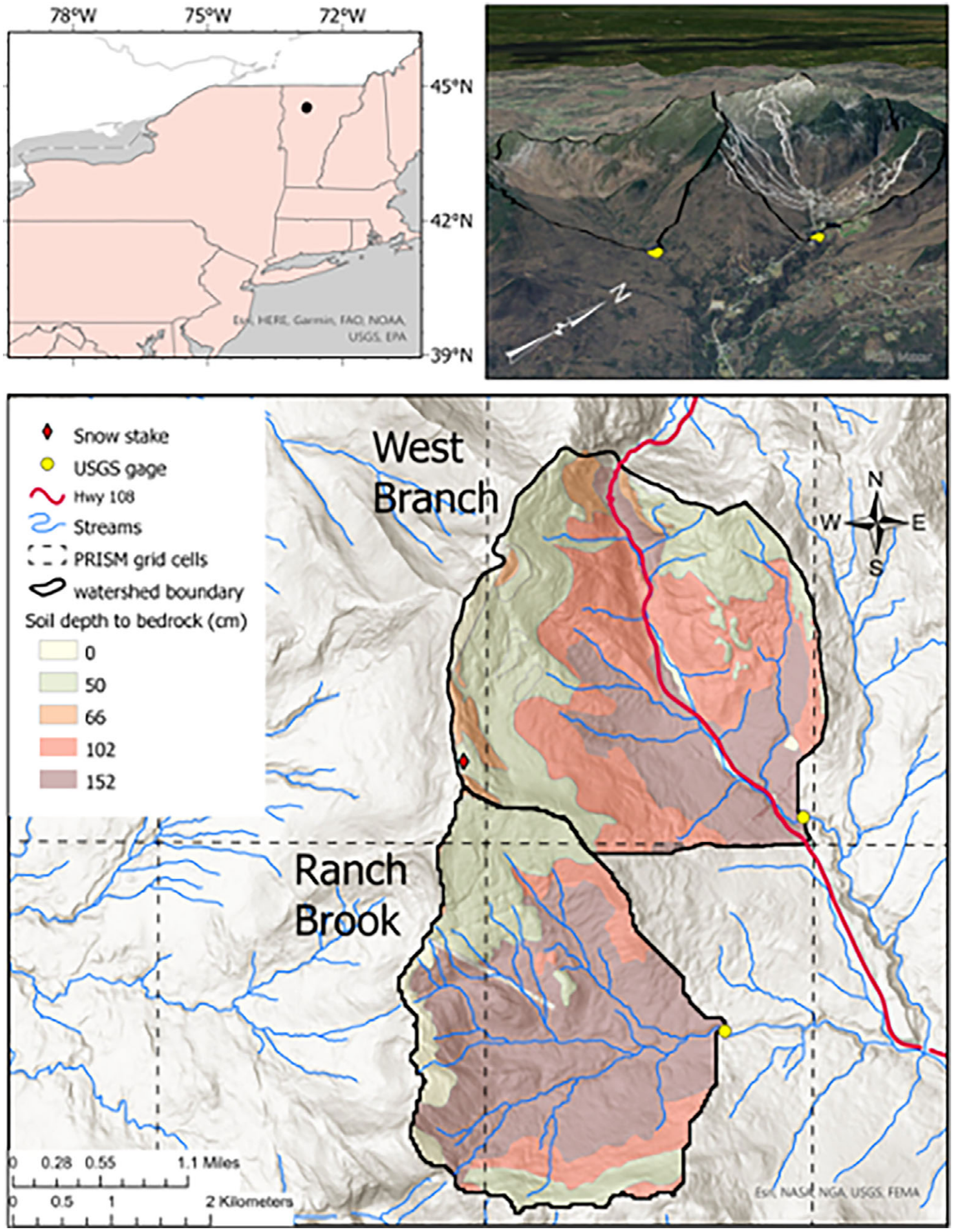

FIGURE 1 Map of Ranch Brook and West Branch catchments near Stowe, Vermont, showing soil depth, gage and snow stake locations. Upper right panel displays a 3-D view looking west showing the West Branch alpine ski trails (see Figure S1 for larger scale view). Roads, streams and soils data displayed on map panels were acquired from https://geodata.vermont.gov/ and are in the public domain. PRISM grid cell extents acquired from https://prism.oregonstate.edu/. Basemap imagery and state boundaries displayed on map panels are the intellectual property of Esri and are used herein under licence. Copyright © 2020 Esri and its licensors with all rights reserved. Remaining spatial data displayed are the property of the investigators and are not under copyright

Little River drains a 12.08-km^2 catchment that is bisected by Vermont State Highway 108 and contains the entire Stowe Mountain Resort on both sides of the highway. The resort started as an alpine ski area and is now a four-season operation with a large base area, golf course and real estate development. West Branch catchment has 6% of its area in alpine tundra. At the start of the study, 11% of its area had been cleared for alpine ski trails and lifts, parking lots and structures, for a total of 17% non-forested area.

The 20-year record of hydrologic measurements presented here spans a period of ski resort development within the West Branch catchment. Stowe Mountain Resort conducted a major expansion on Spruce Peak (east side of State Highway 108) from 2004 to 2008, including new ski trails, a greatly enlarged lodge and base area, vacation homes, a nine-hole golf course and a 435 000-m^3 storage reservoir for snowmaking water. Water is withdrawn from West Branch at a point above the streamflow gage and ultimately redeposited as snow on the mountain within the catchment. A stormwater detention system was built to reduce peak flows from the increased impervious surface area. After expansion, the percentage of land cleared for the ski resort increased from 11% to 18%, for a total of 24% non-forested area. The expansion represented a new disturbance that began following 3 years of baseline monitoring.

The two catchments share a boundary and have similar geology, size, elevation, slope, aspect, soils and forest cover. West Branch is somewhat higher, ranging from 404 to 1340 m, while Ranch Brook ranges from 378 to 1173 m. The bedrock geology of both catchments is quartz-muscovite-chlorite and gneiss and pyritic schist of the Fayston and Hazens Notch formations (Christman, 1959;

Thompson & Thompson, 1998). Soils in both catchments are moderately well drained, coarse loamy to fine sandy loam Spodosols with up to 35% clasts. Below 600 m, dense glacial till, with moderate slow drainage, forms a prominent Cd horizon at about 70 cm (Allen, 1989; Babcock, 1981). Soil unit descriptions from the Natural Resources Conservation Service (https://geodata.vermont.gov/datasets/vt-data-nrcs-soil-survey-units) indicate that soils are thinner within the West Branch than in the Ranch Brook catchment. Soils are greater than 102 cm thick in 59% of Ranch Brook but only 27% of West Branch (Figure 1). A northern hardwood forest of sugar maple (*Acer saccharum*), red maple (*Acer rubrum*), yellow birch (*Betula alleghaniensis*), paper birch (*Betula papyrifera*) and American beech (*Fagus grandifolia*) dominates at lower elevations (<750 m) while red spruce (*Picea rubens*) and balsam fir (*Abies balsamea*) dominates at higher elevations (Ross & Wemple, 2011).

Precipitation is relatively evenly distributed throughout the year (Wemple et al., 2007). The estimated proportion of annual precipitation as snow ranges from 25% at the gage elevations (Shanley et al., 2015) to 40% near the summit (computed from snow stake data). Estimated mean annual temperature is 5°C at the base and 1°C at the summit (computed from Shanley et al., 2015). The Mt. Mansfield massif which contains the two catchments is one of the snowiest spots in the northeastern USA. A snow stake (Figure 1) established near the summit in 1951 is monitored daily by the National Weather Service (NWS). Snow can be present every month except July and August. The stake is sited in a protected alcove that tends to collect and conserve snow, and is read for depth and not water equivalent, but it is a reliable indicator of the general snowpack magnitude. Snowmelt typically occurs from mid-March through April on the main mountain, and lasts well into May at the stake.

3 | METHODS

The two streamgages in this study are operated following USGS protocols (Turnipseed & Sauer, 2010). Ranch Brook has a natural control. The original West Branch gage (2000–2004) utilized a thin-plate rectangular weir which the resort and its consultants had previously used to measure flow and ensure compliance with minimum flow requirements. A gate in the weir pool allowed the resort to divert streamwater into a streamside pond as the water source for mountain snowmaking. As part of the expansion, the resort constructed a larger storage pond upslope in 2004–2005. Water was still removed primarily during the snowmaking season, but the additional storage allowed for more strategic timing of the water withdrawal to avoid the low flows induced by the more 'on-demand' nature of pumping prior to 2005. The old snowmaking pond was re-purposed as a stormwater retention reservoir, with a new outlet that bypassed the weir. To capture this bypass flow, USGS moved the gage about 300 m downstream on 17 November 2004.

At both gages, gage height is measured with a pressure transducer. Discharge measurements several times per year are used to construct and modify, as necessary, the empirical stage-discharge relation. The discharge data are quality assured on an ongoing basis, including adjustments and estimates for backwater due to ice, before final approval. For comparing the two catchments, we normalized the flow to catchment area, yielding instantaneous specific discharge in units of mm h^{-1}, and daily, monthly or annual total runoff in mm.

In the first 3 years of the study, we characterized precipitation using a precipitation gage at the West Branch streamgage, the NWS gage at the summit, and elevational transects in each catchment of summer rain gages and spring snow water equivalent measurements (Wemple et al., 2007). The West Branch precipitation gage was discontinued after September 2003, so we relied on the NWS summit station and the nearby Morrisville airport (223 m, 12 km to the east). We scaled the annual lapse rate between these two sites to account for the known higher lapse rate on the mountain, based on 2 years of precipitation at the West Branch gage (Wemple et al., 2007). We apportioned the result to the catchment hypsometries. However, because this calculation was based on a single mountain lapse rate for both catchments, we also derived precipitation from PRISM (https://prism.oregonstate.edu/), which accounts for windward-leeward effects and other aspects of complex terrain. The resolution of PRISM is 4 km, thus the 4-km × 4-km grid cells are about the size of the watersheds and each watershed was fairly well framed by a single grid cell, so we simply used the respective values for those cells (Figure 1).

To assess hydrologic effects of the major phase of the resort expansion of 2004–2008, and long-term trends in flow conditions, we used a range of analytical approaches. We compared flow duration curves for pre-expansion (Water Years 2001–2003; a Water Year [WY] runs from October of the prior year through September of the designated year) to a comparable period (closest match in 3-year flow totals) in the post-expansion period. We examined cumulative flow differences between the two watersheds using a self-organizing map to classify each day surrounding the snowmelt period (Supporting Information Section 1). Because the increase in impervious and compacted surfaces with the resort expansion was expected to cause more quickflow and increased flashiness, we assessed flashiness with the Richards-Baker index (Baker et al., 2004; Holko et al., 2011), calculated for each year as the sum of the absolute differences in successive daily flows divided by the total annual flow. For all assessments of the effects of snow and snowmelt on hydrology, we used the maximum snow depth at the summit snow stake (Figure 2) as a proxy for total meltwater input.

4 | RESULTS

4.1 | Precipitation and runoff

As the highest mountain in Vermont, Mt. Mansfield receives a high amount of precipitation. Annual precipitation averaged 2013 ± 253 mm (*SD*) at the near-summit station (1204 m) and 879 ± 236 at the nearby Morrisville Airport (223 m). There was no trend in the frequency of high-precipitation days at either site (Figure S2). Areal

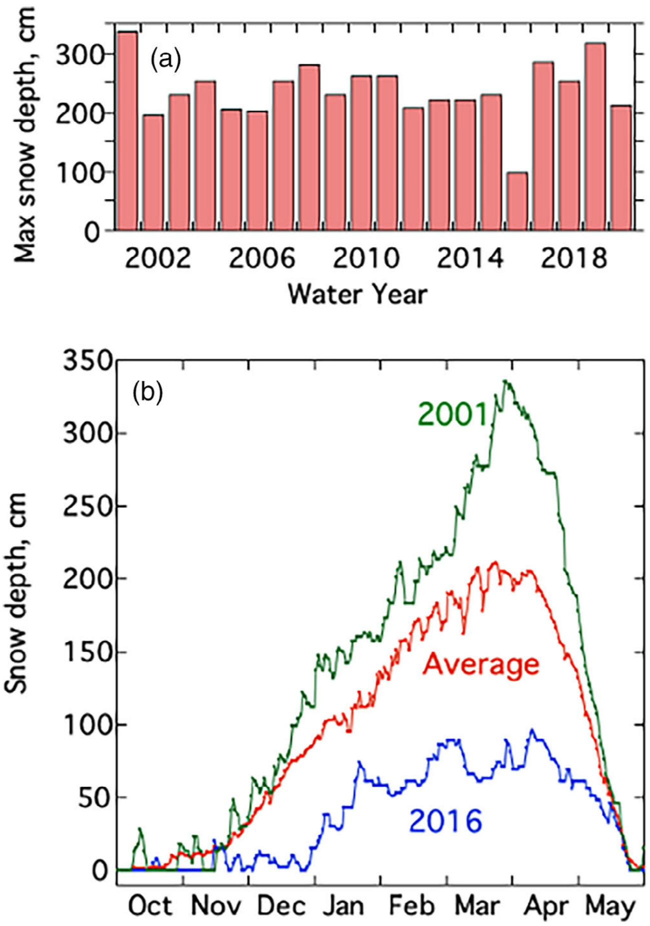

FIGURE 2 Mount Mansfield summit snow stake near Stowe, Vermont. (a) Annual maximum snow depth, and (b) plot of highest (2001) and lowest (2016) snow depth years, and average depth for the 20 years of this study. Average depth plot represents only 19 winter seasons, 2001–2019, because of incomplete data in 2020. Years here refer to the main part of the winter, after 1 January

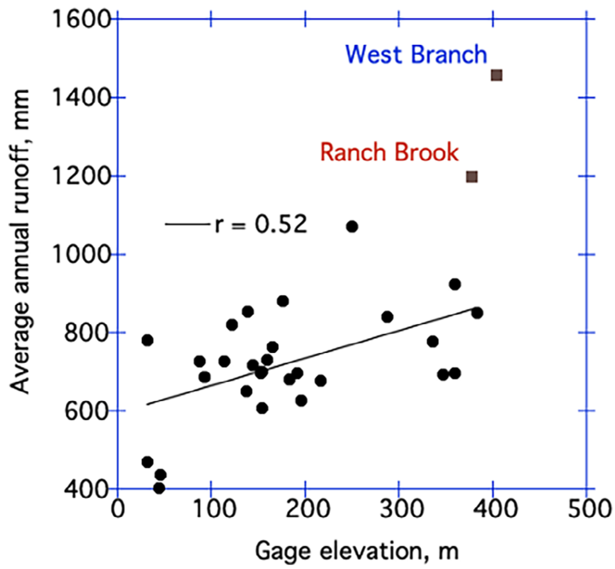

FIGURE 3 Annual runoff versus gage elevation for regional streams (Vermont, New Hampshire, western Massachusetts, northeastern New York) presented by Olson and Bent (2013)

distribution of precipitation computed from a lapse rate using the summit and Morrisville stations (Figure S3) was too low and too variable to support the magnitude of observed runoff. Based on PRISM, West Branch had nearly 200 mm greater average annual precipitation than Ranch Brook (1783 mm vs. 1587 mm). The PRISM-based precipitation was also a consistent predictor of annual runoff (Figure S4). The slopes of each relation were near 1.0, yielding annual precipitation minus runoff (P-R) values of ~300 mm at West Branch and ~400 mm at Ranch Brook.

During the 20 years, the maximum snow depth at the summit stake ranged widely from 97 cm (2016) to 335 cm (2001) (Figure 2), with a 20-year average of 237 ± 50 cm. Peak snow accumulation occurs on average on March 27, with a standard deviation of 16 days. Assuming a snow density of 0.3, typical for a late season pack that is beginning to ripen, the average water stored in the snowpack was about 700 mm, or about one third of the annual precipitation. Our own elevational snow surveys conducted in some years confirmed a snow density close to 0.3 near peak accumulation (Figure S5).

Given its relatively high precipitation enhanced by orographic effect at high elevation, annual runoff at both West Branch and Ranch Brook was consistently above regional averages (Figure 3), a pattern that had emerged in the first 3 years of gaging (Wemple et al., 2007). Annual runoff was anomalously high for the gage elevations (Figure 3). The relation may be skewed because the Mt. Mansfield catchments have high proportions of high-elevation, high-precipitation areas in their catchments compared to other sites. Precipitation stored as snow in the winter months runs off over a fairly short period in spring, causing high runoff and groundwater recharge that sustains base flow through the spring and summer months.

4.2 | Flow differential in the paired catchments

The pattern of markedly higher runoff at West Branch, the developed catchment, observed in the first 3 years of monitoring (Wemple et al., 2007), persisted through 17 additional years of record. Runoff for the entire period was 21% greater (246 mm/year) at West Branch. The differential runoff had high interannual variability, ranging from 10% to 42% (Figure 4) with a standard deviation of 8.0%. The annual runoff differential between Ranch Brook and West Branch arises primarily during spring snowmelt and summer (Figure 5). On average, runoff from the two catchments was fairly equal from mid-November to mid-March. The low and occasional slight negative differentials during these months were sustained at least in part by the average 80 mm withdrawn annually mostly for snowmaking at West Branch (Figure S6; computed from regulatory compliance reports to the Vermont Department of Environmental Conservation [https://anrgeodata.vermont.gov/datasets/snowmaking-withdrawal]).

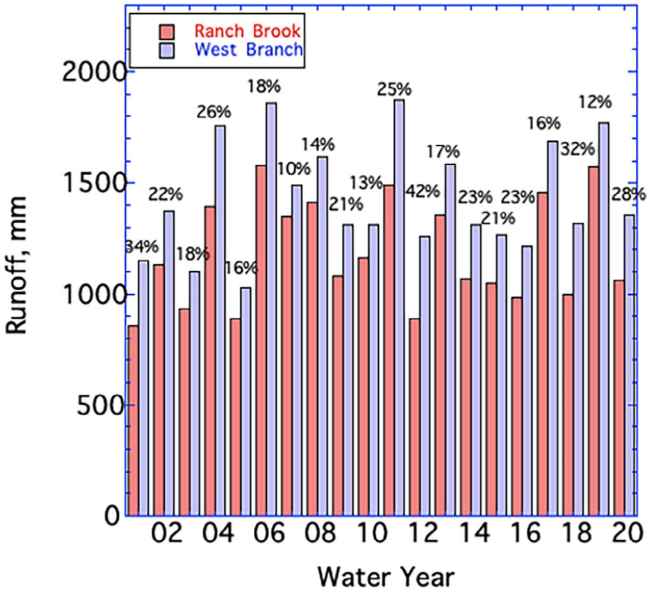

FIGURE 4 Annual runoff (mm) at Ranch Brook and West Branch, annotated with percent difference relative to Ranch Brook runoff, Water Years 2001–2020

The WY2001–WY2003 pre-expansion period was fairly dry, so we paired it with the comparably dry WY2014–WY2016 (total flow 6.5% greater at Ranch Brook) post-expansion period to compare flow duration curves (Figure 6). The Ranch Brook curves were quite similar for the two periods (Figure S7), while West Branch flows increased considerably in the more recent period at flow durations >60% (lowest flows; Figure S7b). This pattern occurred despite higher withdrawals overall (Figure S6), but the greater snowmaking water storage capacity achieved during resort expansion resulted in less direct streamwater withdrawal during times of lower runoff. West Branch had higher runoff at 10%–40% flow duration during both periods, but the curves converged near median runoff and at the highest runoff (Figure 6a,b). Comparing flow duration for individual years, we see the crossover to higher low flows at West Branch occurred starting in WY2005 (Figure 6c). Median runoff (50% duration) was generally higher at West Branch but the two sites converged in the middle years of the record (Figure 6c). West Branch had consistently slightly greater flows over the higher runoff range as shown at the 10th percentile, but the two sites again converged in most years on the very highest runoff days, except during the middle years of the record

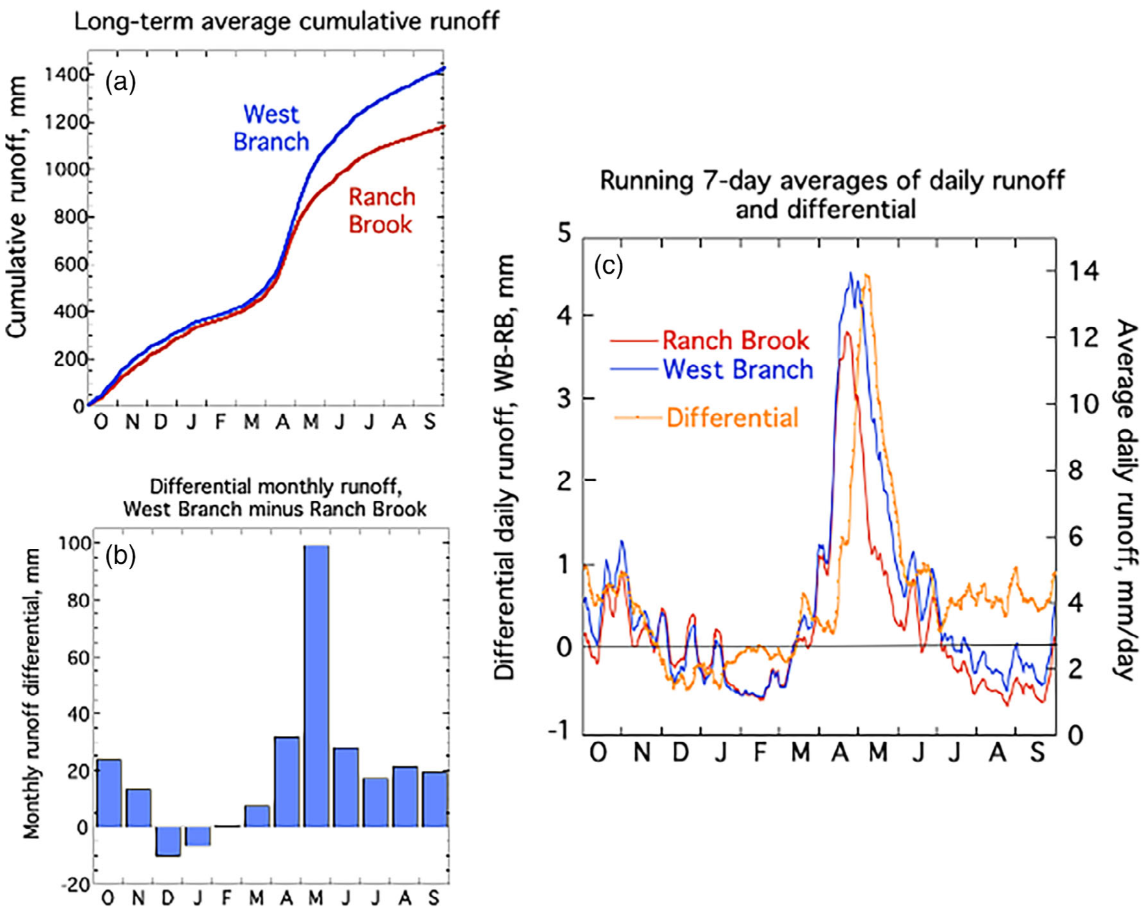

FIGURE 5 (a) Average (Water Years 2001–2020) cumulative runoff through the water year, and (b) average differential monthly runoff, West Branch minus Ranch Brook, between the two catchments; (c) 7-day moving average daily runoff at each gage, with 7-day moving average of the daily runoff differential between the two catchments

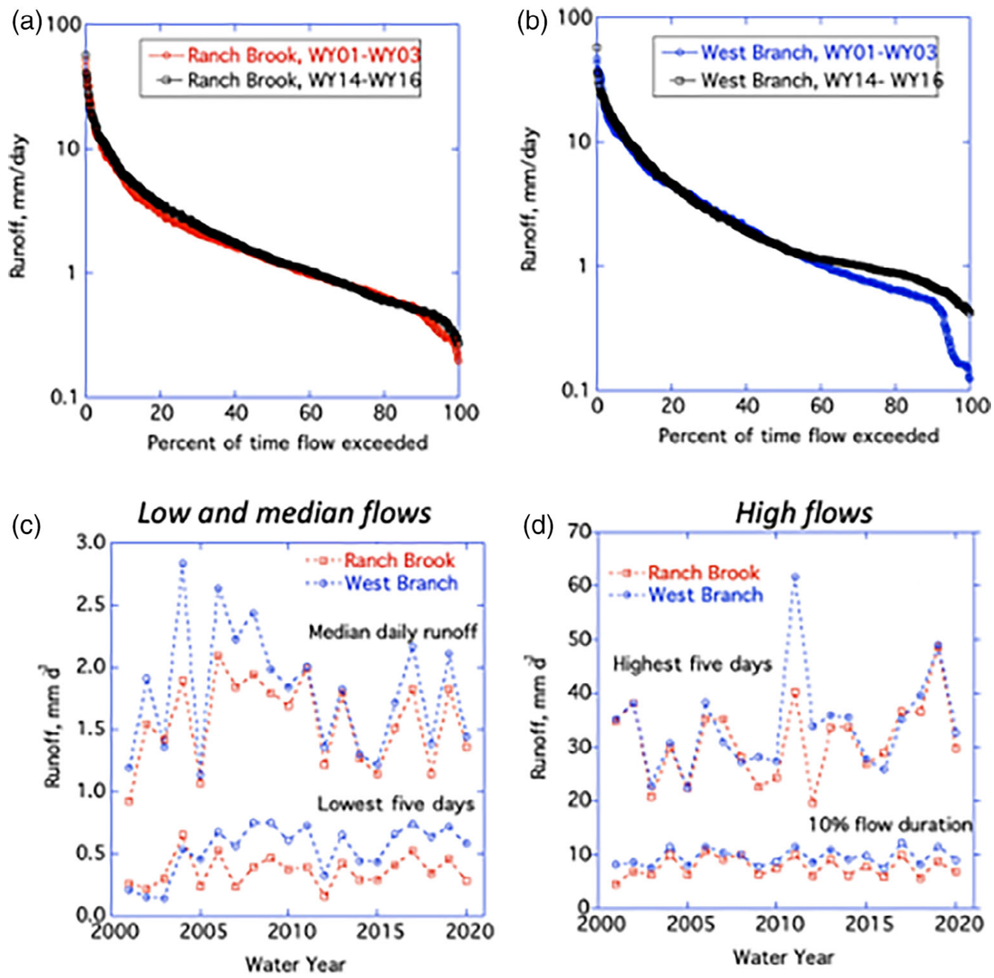

FIGURE 6 Runoff duration curves from daily runoff for Water Years 2001–2003 and 2014–2016 at (a) Ranch Brook and (b) West Branch near Stowe, Vermont; (c) median daily runoff and average of five lowest runoff days, and (d) average of five highest runoff days and 10% exceedance daily runoff for Water Years 2001–2020

when West Branch flows were greater (Figure 6d). Comparative flows in years of strongly contrasting differentials are depicted in Figure S8.

4.3 | Snowmelt and effect of snowmaking

The late snowmelt period (mid-April through May) was the clear point of divergence of the cumulative runoff curves (Figure 5). On average the daily runoff in the two catchments peaked near the same time in late April, but West Branch runoff rose at a faster pace starting on the rising limb of the hydrograph and accelerating on the falling limb, such that the differential peaked at 5 mm about a week after the snowmelt peak (Figure 5). The differential fell back to ~1 mm over the next month of flow recession, where it remained through the summer, but the coincidence of the highest differential runoff and highest overall runoff drives most of the overall average annual 246 mm differential.

The snowmelt centre of mass (midpoint of cumulative flow from 1 April to 30 June) occurred between late April and late May and was on average 2.6 days earlier at Ranch Brook (Figure S9). Interestingly, the only years where the centre of mass was later at Ranch Brook, each by 1 day, were the 4 years with the latest centre of mass date. There was no significant shift in the timing of the centre of mass during the study duration. The amount of annual water withdrawal varied little from year to year (Figure S6), and thus was not a driver of snowmelt amount or timing. The May runoff differential was weakly related to summit snow depth (Figure S10). In all years, the May differential exceeded the total annual water withdrawn (Figure 5 and Table 1). Total runoff differential over the melt period was strongly keyed to rainfall amount (removing one outlier [2012], $r^2 = 0.31$, $p = 0.014$; Figure 7; see also Figures S11 and S12).

4.4 | High-flow event dynamics

West Branch generally had higher runoff across the flow duration curve (Figure 6), but specific high-flow events had higher peak runoff at Ranch Brook (Figure S13). These events were typically among the largest, and included early snowmelt peaks. In fact, Ranch Brook had a higher annual peak daily runoff during 8 of the 20 years of record, and higher instantaneous peak runoff rates during 7 of the 20 years (Figure 8). Several noteworthy peak flows occurred during the middle part of the period. From 2009 to 2011, West Branch recorded five of the eight highest peak flows in the 20-year record. Ranch Brook also had its three highest peak flows during this period. Water Year 2011

TABLE 1 Stream withdrawals from West Branch in Stowe, Vermont, for snowmaking and golf course irrigation, compared to West Branch May runoff

Water Year	Total snowmaking usage (mm)	Golf course irrigation (mm)	May runoff (mm)
1996	51.4		
1997	60.0		
1998	55.0		
1999	53.4		
2000	51.3		
2001	45.8		304.4
2002	43.4		266.7
2003	51.5		199.2
2004	52.8		247.8
2005	55.3		141.9
2006	81.6		351.0
2007	76.4	3.4	247.8
2008	80.8	1.8	191.6
2009	83.1	1.5	266.8
2010	78.2	2.0	174.7
2011	82.3	1.2	443.8
2012	69.1	3.2	225.7
2013	88.4	1.8	353.2
2014	95.7	1.6	369.7
2015	87.0	2.7	316.3
2016	96.1	2.2	142.4
2017	84.5	No data	296.0
2018	75.8	2.6	414.4
2019	61.3	No data	405.5
2020			314.2

Note: All values expressed in terms of mm applied over the entire West Branch watershed.

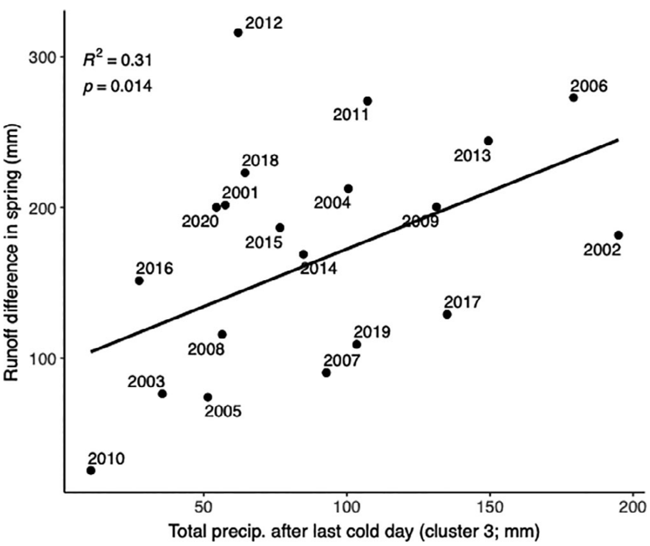

FIGURE 7 Relationship between cumulative runoff differences in Ranch Brook and West Branch near Stowe, Vermont from the beginning of the Water Year until June 2 and the total volume of precipitation that fell after the last day that was classified as very cold (cluster 3) by the self-organizing map (see Supporting Information Section 1)

had events of 4%–6% annual exceedance probability and WY2010 had events of 3%–4% annual exceedance probability based on the analysis of Olson and Bent (2013).

Interestingly, the highest peaks at these gages did not occur during the large frontal or cyclonic events that caused statewide and regional flooding. While these regional events did generate notable peaks at the two gages, the highest peaks were typically associated with highly localized 'stalled cells' that produced prodigious amounts of rainfall during short time periods. These events were primarily warm season convective storms. The localized nature and spatial heterogeneity of these storms is underscored by the fact that during 9 of the 20 years, the annual peak flow at the two gages occurred from different events (Figure 8b).

There was no temporal trend in annual runoff, but annual peak flows showed an increasing though non-significant linear trend ($r = 0.28$, $p = 0.23$ at Ranch Brook; $r = 0.37$, $p = 0.11$ at West Branch) during the 20-year record (Figure 8a). However, both catchments had a trend of increased flashiness over time. Ranch Brook had consistently greater flashiness and its rate of increase was also faster. There was no discernible difference in the flashiness pattern or rate of increase at West Branch during the expansion (Figure 9).

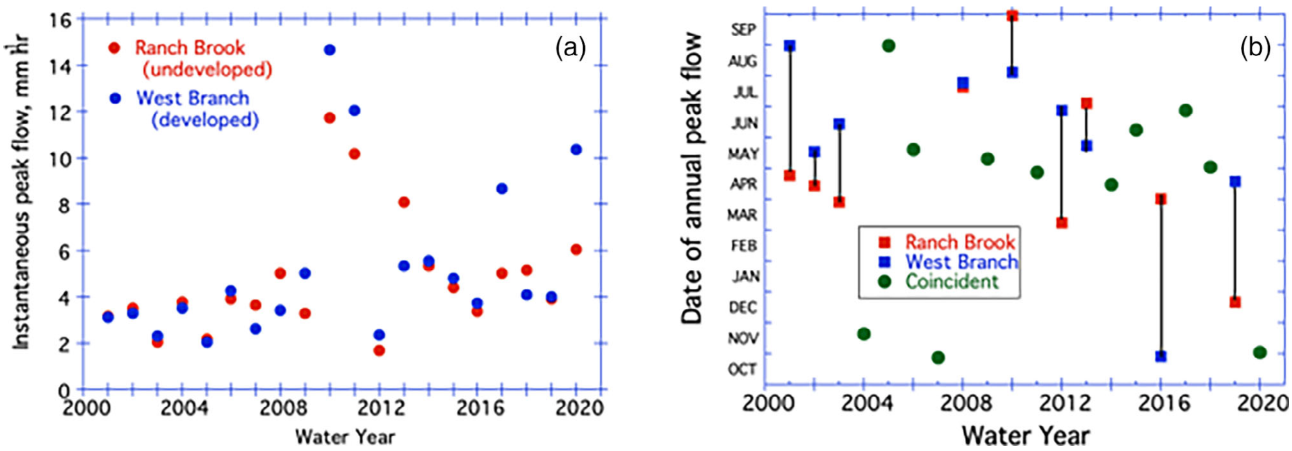

FIGURE 8 (a) Magnitude and (b) date of annual peak runoff at Ranch Brook and West Branch near Stowe, Vermont, for each Water Year

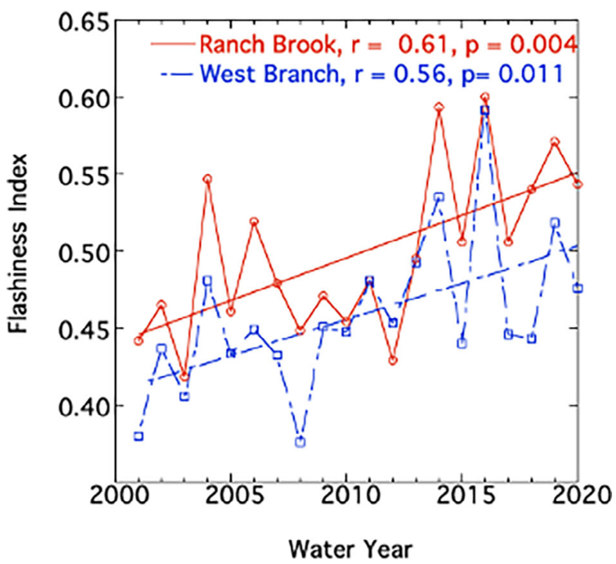

FIGURE 9 Richards-Baker Flashiness index by Water Year at Ranch Brook and West Branch near Stowe, Vermont

5 | DISCUSSION

5.1 | Monitoring in the mountains

The impetus for this research was the paucity of science on the effects of development in the mountain landscape. We used a conventional paired-catchment design to evaluate the effects of a ski resort and its expansion. In so doing, we learned a great deal about the natural hydrologic functioning of these systems that underscores the value of acquiring baseline information and evaluating how mountain ecosystems will respond to development and climate change. Our 20 years of monitoring is too short to assess trends, but some of the incipient trends we observed, such as increasing stream flashiness and high interannual variability in hydrologic response are consistent with what we can expect in future climates (Huntington, 2006; Koutsoyiannis, 2020). The extremes also allow us to project future climate, for example, our very low-snow year 2016 as a proxy for future low-snow years. In Wemple et al. (2007), we established a pre-expansion baseline on solute chemistry and suspended sediment, including during high-flow events. The State of Vermont has adopted the Ranch Brook gage as one of its sentinel sites for regular macroinvertebrate and water quality monitoring (https://anrweb.vt.gov/DEC/IWIS/), where biological and chemical change can be interpreted in the context of hydrologic change (Stamp et al., 2020).

5.2 | Hydrologic differences between the two catchments

The runoff differential averaging 246 mm annually between the two catchments is likely too high to attribute solely to the ski resort. Applying results from previous studies to the area of affected land in the catchment, less than 100 mm annually can be ascribed to reduced evapotranspiration from conversion of forest to ski trails (Supporting Information Section 2). The precipitation lapse rate of 0.89 mm m^{-1} $year^{-1}$ reported in Wemple et al. (2007) and applied to the average precipitation at the summit and the catchment hypsometries accounts for 45 mm greater precipitation at West Branch. The PRISM-derived precipitation, which considers not only elevation but terrain complexity, estimates 200 mm greater annual precipitation at West Branch. The prominence of the Mt. Mansfield massif in the northwesterly airflow may enhance lee-side precipitation, while the Ranch Brook catchment lies somewhat in its rain shadow to the south. This orientation could cause an effective steepening of the lapse rate at West Branch and a corresponding flattening at Ranch Brook. Most of the flow differential arises during snowmelt, suggesting enhanced snow capture at West Branch. Winds out of the north and west along the exposed Mt. Mansfield ridgeline may cause considerable redeposition of snow from the west side of the ridge into the leeward West Branch catchment. This scenario was supported by comparison of adjacent leeward and windward PRISM cell precipitation, which revealed a 2.5% leeward enhancement at West Branch and a 5.8% windward enhancement at Ranch Brook (Figure S14).

A key aspect of the runoff differential is its wide year-to-year variability. The high interannual variability in the runoff differential (Figure 4) is consistent with the spatial variability of precipitation and the hit-or-miss nature of storms. Goodrich et al. (1995) found high spatial variability of rainfall in rugged terrain at points as little as 100 m apart; uneven rainfall distribution confounded their attempts to model runoff for a 4.4-ha catchment. Tetzlaff and Uhlenbrook (2005) analysed radar and concluded that the scale of spatial variability was finer than even a dense network of precipitation gages could capture, and likewise argued that incorporating this variability was critical to modelling catchment streamflow response. Greater hydrologic variability is an expected outcome of a warming climate (Huntington, 2006).

5.3 | Effect of resort expansion

The ski resort was well established before our study began, but the resort expansion provides an appropriate application of the paired-catchment approach. Our main hypothesis held that the impervious and compacted surfaces such as resort roads, parking lots and ski trails would enhance runoff at the expense of recharge at West Branch. This alteration to the hydrologic regime should skew the flow duration curves toward higher values at low exceedances and lower values at higher exceedances. However, these expected hydrologic changes did not occur. The consistency of the flow differential across the flow regime, and the general agreement of the pre- and post-expansion flow distributions (Figure 6), suggest that stormwater management within the expanded resort footprint and detention storage in the stormwater pond may help to attenuate flow at the scale of the West Branch gage. However, this larger scale outcome does not preclude localized erosion by stormwater before it enters the system. As well, the hydrologic behaviour does not explicitly address the impaired water quality from suspended sediment, deicing salts and elevated nitrate documented in our earlier study (Wemple et al., 2007).

Focusing of runoff by impervious surfaces at West Branch should cause the greatest runoff differential on the highest runoff days, but on those days the runoff differential actually vanished (Figure 6). These days were often during the peak snowmelt period, which suggests that Ranch Brook must overcome a saturation deficit threshold before it can yield water at the same rate as West Branch. Greater soil water storage capacity may keep Ranch Brook consistently below this threshold over the rest of the flow regime, while West Branch shows higher runoff due to more frequent 'fill and spill' behaviour (Aulenbach et al., 2021). Analogously, we expected that the flashiness index would tend to be greater at West Branch and would show a step increase after the expansion, but neither of these patterns occurred (Figure 9). The pattern of increasing year-to-year flashiness, with a higher rate of increase in the undeveloped Ranch Brook catchment, suggests that at the catchment scale, increasing climatic variability is having a greater effect on the hydrology of these systems than the ski resort development. In another possible indicator of climatic influence on hydrology, at Ranch Brook the February median flow, which is used as a minimum flow to maintain for snowmaking, has increased during the study period (Figure S15).

5.4 | Management in the mountains

Mountains are sensitive environments facing multiple stresses from development, resource extraction and climate change. Integrating stormwater management in mountain development may minimize alterations to the flow regimes, but water quality degradation and sedimentation may be more difficult to avoid (Wemple et al., 2007). Increasingly strong storms from climate change elevate the challenge. The series of large events in 2009–2011 (Figure 8) were low probability storms (Olson & Bent, 2013) and were consistent with climate change projections of increasing intensity and variability of storm events (Campbell et al., 2011). The largest events were so localized that they generated quite different precipitation amounts in the two catchments. Their impact was highly attenuated at the scale of the larger regional valleys, so they are poorly captured by conventional streamgaging networks (Holko et al., 2014). The pressure on high-elevation ecosystems warrants continued investment in high-elevation catchment monitoring, to better understand precipitation and flow regimes, and to calibrate flood prediction models.

6 | CONCLUSIONS

In the only known paired-catchment study to directly assess the effect of a mountain ski resort expansion, the resort catchment yielded 21% greater runoff during 20 years of record. The difference was too great to attribute solely to the development, and is likely explained by enhanced precipitation capture, including snow redeposition, due to its higher elevation and more prominent exposure to incoming air masses, A more rapid 'fill and spill' cycle at West Branch owing to its thinner soils may also contribute to its greater runoff. A major resort build-out, which expanded non-forested area from 17% to 24% of the catchment and included stormwater management, had little hydrologic effect at the scale of the catchment, though localized effects of impervious surfaces may have occurred. Climatic variability and extreme precipitation events had a greater effect on flows. Some of these events were localized to the mountain and had limited impact in the downstream valleys. Responsible development in our mountain landscapes must be predicated on a knowledge of the hydrologic impacts, including consequences of too much or too little water. Speaking to the challenges of modelling mountain hydrology, the storied Czech hydrologist Vit Klemeš said 'The mountains don't give up their secrets easily' (Klemeš, 1990). But discovering their secrets is the key to protecting them. Our monitoring and scientific understanding of the hydrologic sensitivity and resiliency of the mountain landscape must keep pace with the pace of development.

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DATA AVAILABILITY STATEMENT

Data for Ranch Brook are publicly accessible at: https://waterdata.usgs.gov/vt/nwis/uv?site_no=04288230. Data for West Branch are publicly accessible at: https://waterdata.usgs.gov/vt/nwis/uv?site_no=04288225.

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