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WATER QUANTITY AND QUALITY IN THE MOUNTAIN ENVIRONMENT

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INTRODUCTION

Mountain streams provide habitat for fish, amphibians, and macroinvertebrates, as well as clean water for human consumption downstream. A healthy mountain stream, which is full of aquatic life and has a characteristic pool and riffle structure, a stable channel, and a gravel substrate, is an indicator of a healthy ecosystem.[1] The water comprising the stream must first pass through the adjacent terrestrial ecosystem which, if healthy, has a vegetation and soil system that buffers extremes in flow and limits erosion.[2] This terrestrial ecosystem, or watershed, acts like a filter, preventing some types and amounts of contaminants from reaching the stream.

The mountain stream is an integrator of processes and activities occurring within the stream's watershed. This means that the condition of the stream at a given point reflects the net effects of all activities upstream. A stream reach may be degraded as a result of disturbance upstream even when the adjacent watershed is healthy. Too much disturbance in the watershed of a stream can destabilize the stream, and this is a major concern in mountain development.[3] Several types of disturbances may lead to increased peak flows and erosion, including forest clearing, soil compaction, and the creation of impervious surfaces, such as roofs and roads.[4] Stream channels adjust to higher flood peaks by incising or widening,

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[1] Flowing water ecosystems are a series of interrelated habitats, including the turbulent riffle and the quiet pool. Riffles are the primary production sites for algae and other invertebrates, while the pools—above and below the riffles—act as catch basins, in which the chemistry, the intensity of the current and the depth are different. Without either habitat, a stream could not maintain proper chemical equilibrium. The overall productivity of a stream is influenced by the bottom. Gravel and rubble bottoms support the most abundant life, as organisms attach to and move on loose gravel, which also provides protective crannies for insect larvae. *See generally* PAUL S. GILLER & BJÖRN MALMQVIST, THE BIOLOGY OF STREAMS AND RIVERS 30–70 (1998); LUNA B. LEOPOLD, A VIEW OF THE RIVER 21–29 (1994).

[2] *See generally* GILLER & MALMQVIST, *supra* note 1, at 3–6; PETER E. BLACK, WATERSHED HYDROLOGY 91–206 (1996).

[3] THOMAS DUNNE & LUNA B. LEOPOLD, WATER IN ENVIRONMENTAL PLANNING 510 (1978) ("Human occupance of land almost always increases the rate of hillslope erosion by significant and sometimes catastrophic amounts.").

[4] *Id.* at 507–17 (describing geological normal and accelerated rates of erosion due to human activity); GILLER & MALMQVIST, *supra* note 1, at 229–30.

causing stream banks to fail.[5] Sediments from runoff over impervious surfaces, combined with sloughing stream bank material, cause stream pools to fill in and fine-textured material to deposit on the gravel stream bed, thus degrading critical fish spawning habitat.[6] This is the worst-case scenario, where the fabric of the stream ecosystem may be said to "unravel."

Despite these concerns, there is a notable lack of significant research on the effects of mountain development on hydrology in the northeastern United States and adjacent Canada. Although researchers have observed stream unraveling in extreme cases of unmitigated disturbance, ski area and mountain resort effects on streams have received little scientific scrutiny, particularly in eastern North America. Thus, policymakers and agencies that issue permits have little scientific information on which to base their decisions. Instead, mountain resort plans are approved based on standard erosion control measures such as stormwater runoff control practices and the retention of forested buffers along stream channels.[7] The effects of these measures are predicted with hydrologic models that are rarely if ever calibrated with site data. Whether these standard erosion control measures are truly appropriate for high-elevation environments is not known.

Part I of this Paper begins with an overview of mountain hydrology and water quality of mountain streams in the natural ecosystem. Part II discusses how alterations to natural systems may affect stream flows, and considers the special case of snowmaking. Part III addresses water quality problems arising from resort development. This is followed by a brief discussion of a new investigation at a Vermont ski resort, designed to help fill the current gap in scientific understanding. In addition, Part III presents some preliminary data on streamflow and water quality from this new study. Finally, this Paper concludes with a discussion of the data gap, and how much scientists can reasonably infer and apply from other studies to the issue of mountain resorts.

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[5] DUNNE & LEOPOLD, *supra* note 3, at 695; *see also* LEOPOLD, *supra* note 1, at 126–31.

[6] DUNNE & LEOPOLD, *supra* note 3 at 714.

[7] Environmental requirements for ski areas usually lack the formality of established Best Management Practices (BMP's) applied to other industries. BMP's are "management, cultural and structural practices that the agricultural scientists, the government or some other planning agency" determine are the most effective and economical methods by which to control erosion and other water quality problems associated with logging and agriculture, without unduly impacting upon the environment. *Best Management Practices at* http://www.ecn.purdue.edu/AGEN521/epadir/erosion/bmps.html (last visited Apr. 9, 2002); *see also* Vermont Natural Resources Council, *Vermont Natural Resources Council's Water Program at* http://www.vnrc.org/water.htm (last visited Apr. 9, 2002). Under Vermont Water Quality Standards, the term "Best Management Practices" is defined as "a practice or combination of practices that may be necessary to prevent or reduce pollution from non-point source wastes to a level consistent with the applicable provisions of these rules." VT. STAT. ANN. tit. 6, § 216 (2001).

I. BASIC MOUNTAIN HYDROLOGY CONCEPTS

Put simply, streamflow is the water left over after natural processes consume water that originally fell as precipitation.[8] In cold-climate mountainous watersheds, including the forested mountains of the northeastern United States and eastern Canada, annual streamflow amounts to roughly half of the annual precipitation.[9] The other half evaporates back to the atmosphere, or is transpired by vegetation.[10] Transpiration is the process by which plants take in water.[11] Some of this water is used in photosynthesis and is incorporated into biomass;[12] the remainder is evaporated from leaf surfaces.[13] When water is plentiful, this process is surprisingly passive; trees act as giant wicks that transfer water from the soil to the atmosphere.[14] When water is scarce, some trees, especially conifers, can effectively shut down photosythesis to limit water loss.[15] Evaporation and transpiration have the common result of returning precipitation to the atmosphere, and are often lumped in the term "evapotranspiration."

The annual climatic cycle drives the precipitation and vegetation cycles, which in turn drive streamflow. In the eastern United States and Canada, precipitation is distributed relatively uniformly throughout the

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[8] This section provides a basic introduction to hydrology. For further reading on basic hydrology we recommend the following: K.N. BROOKS ET AL., HYDROLOGY AND MANAGEMENT OF WATERSHEDS (1991); J.M. Buttle, *Fundamentals of Small Catchment Hydrology*, *in* ISOTOPES IN CATCHMENT HYDROLOGY 1 (C. Kendall & J.J. McDonnell eds., 1998); S. LAWRENCE DINGMAN, PHYSICAL HYDROLOGY (2002); DUNNE & LEOPOLD, *supra* note 3; G.M. HORNBERGER ET AL., ELEMENTS OF PHYSICAL HYDROLOGY (1998); LUNA B. LEOPOLD, WATER, RIVERS AND CREEKS (1997); M. Bonnell, *Progress in the Understanding of Runoff Generation Dynamics in Forests*, 150 J. HYDROLOGY 217 (1993); M. Bonnell, *Selected Changes in Runoff Generation Research In Forests From the Hillslope to Headwater Drainage Basin Scale*, 34 J. AM. WATER RESOURCES ASS'N 765 (1998). A monograph geared toward mountain hydrology is E. WOHL, AMERICAN GEOPHYSICAL UNION, WATER RESOURCES MONOGRAPH 14: MOUNTAIN RIVERS (2000). For a very readable and comprehensive treatment of fresh water hydrology for those with a limited science background, please see E.L. PIELOU, FRESHWATER (1998).

[9] GENE E. LIKENS & F. HERBERT BORMANN, BIOGEOCHEMISTRY OF A FORESTED ECOSYSTEM 16, 22–23 (2d ed. 1995) (summarizing results from a long term study at Hubbard Brook in New Hampshire).

[10] *Id.*

[11] DINGMAN, *supra* note 8, at 275, 277.

[12] *Id.* Biomass is any biological material. In ecological studies, the dry mass of living organisms in a specified area is often expressed as grams of biomass per square meter. BRUCE WYMAN & L. HAROLD STEVENSON, THE FACTS ON FILE DICTIONARY OF ENVIRONMENTAL SCIENCE 47 (2000).

[13] DINGMAN, *supra* note 8, at 275.

[14] *Id.* at 275–77.

[15] E.D. Schulze et al., *Plant Water Balance*, 37 BIOSCIENCE 30, 34 (1987); *see also* B.J. Yoder et al., *Evidence of Reduced Photosynthetic Rates in Old Trees*, 40 FOREST SCI. 513, 524–25 (1994).

year; there is no distinctive dry season or rainy season.[16] In the fall, the vegetation demand for water decreases sharply, allowing streamflow to recover from its summer minimum.[17] In winter, however, most of the precipitation falls as snow and is stored in the snowpack, causing streamflow to decrease again through February, punctuated by occasional midwinter thaws.[18] In spring, several months of accumulated snow is released in a relatively short period, causing sustained high flow.[19] Through the summer, flow gradually decreases as high vegetative demand consumes most rainfall and depletes groundwater storage.[20] Rainfall intensity is

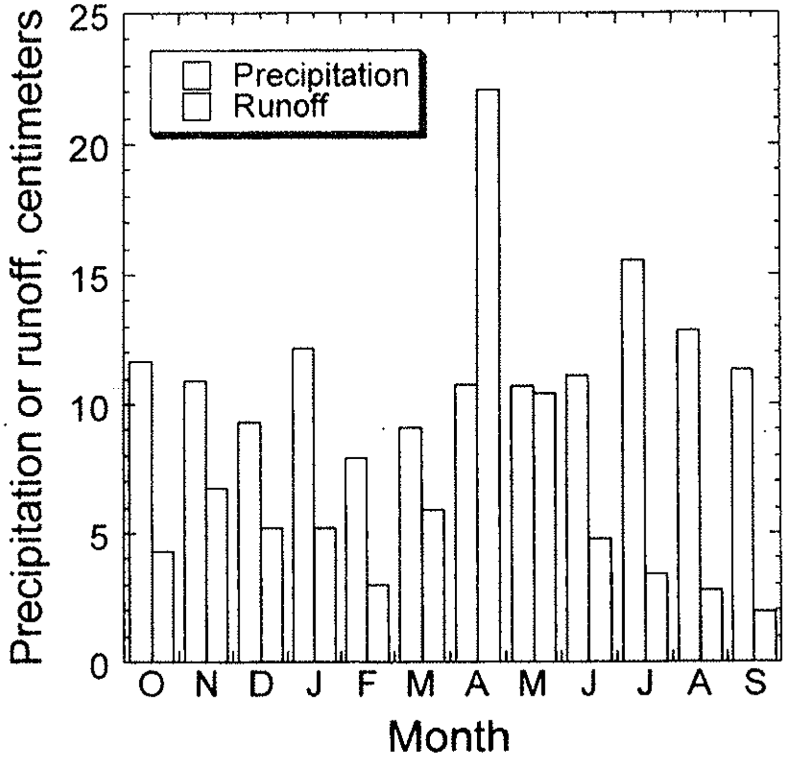

Figure 1. **Typical annual cycle of precipitation and streamflow, based on eight years of data (1991-1998) from Sleepers River Research Watershed, Danville, Vermont.**

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[16] LEOPOLD, *supra* note 8, at 185.

[17] LIKENS & BORMANN, *supra* note 9, at 22; *see also* DUNNE & LEOPOLD, *supra* note 3, at 466.

[18] *See, e.g.*, BLACK, *supra* note 2, at 251–52 (discussing seasonal runoff patterns in the Mohawk River valley of New York). In northern Vermont, twenty-five to thirty-five percent of the annual precipitation occurs as snow. DUNNE & LEOPOLD, *supra* note 3, at 465.

[19] BLACK, *supra* note 2, at 251–52.

[20] *Id.*; *see generally* DUNNE & LEOPOLD, *supra* note 3, at 126–28.

highest in summer,[21] and intense storms can cause high flow peaks, but annual peak flow could occur as the result of a large rain-on-snow event. In spring, peak flows result from combined rain and snowmelt, especially after prior snowmelt has saturated the soil. In summer, peak flows result from intense cloudbursts, which are usually localized, and in the fall, they result from prolonged rainfall events, such as hurricanes [Figure 1].

The above discussion is generic to the entire region of the northeastern United States and eastern Canada. However, conditions differ from one mountain range to another. Considering the hydrologic balance, precipitation increases with elevation, on average about twenty centimeters per three hundred meters (eight inches per one thousand feet) on an annual basis.[22] Thus, the summit of Mt. Mansfield in Vermont receives about two times as much annual precipitation as Burlington; one hundred ninety-eight centimeters (seventy-eight inches) as compared to ninety-one centimeters (thirty-six inches).[23] Another important difference is that a much higher percentage of the precipitation falls as snow at the summit, which affects the timing and magnitude of the spring runoff peak.[24] Summer convective storm cells can often stall in the mountains, producing extremely high rainfall amounts.[25] Such storms have caused extensive flooding in Vermont in recent years.[26] While precipitation increases with elevation, evapotranspiration decreases with elevation, because the growing season becomes shorter and forest growth is less vigorous due to climatic stress and poor soil conditions. With relatively higher precipitation and lower water demand by trees, mountain environments yield a considerably higher amount of streamflow for a given area of land than lowland areas.[27]

Further contrasts emerge in how the mountain landscape processes this high volume of streamflow. Mountains generally have steep slopes and thin soils, a combination conducive to rapid delivery of water to stream

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[21] Nat'l Weather Service Forecast Office, *Detailed Climatological Information for Burlington: Top 10 Seasonal Precipitation Totals*, *at* http://www.erh.noaa.gov/er/btv/climo/seapcpn.txt (showing largest and smallest precipitation totals for each season, by year) (last visited Sept. 13, 2002).

[22] DINGMAN, *supra* note 8, at 104.

[23] Nat'l Weather Serv. Forecast Office, *Average Annual Precipitation Map: Vermont*, *at* http://www.erh.noaa.gov/er/btv/images/vt_pcpn.gif (last visited Sept. 13, 2002).

[24] DUNNE & LEOPOLD, *supra* note 3, at 481.

[25] *See* WYMAN & STEVENSON, *supra* note 12, at 272. Orographic lifting is the upward movement of air when currents in the atmosphere encounter mountains. As the air expands and then cools, the result is precipitation. *Id.* "Orographic precipitation is more likely to be general and prolonged than showery and brief because there is a relatively steady upslope flow of air [traveling over the mountains]." TOM L. MCKNIGHT, PHYSICAL GEOGRAPHY: A LANDSCAPE APPRECIATION 155 (1993).

[26] VERMONT AGENCY OF NATURAL RESOURCES, OPTIONS FOR STATE FLOOD CONTROL POLICIES AND A FLOOD CONTROL PROGRAM 2 (1999).

[27] DINGMAN, *supra* note 8, at 95; S. Lawrence Dingman, *Elevation: A Major Influence On the Hydrology of New Hampshire and Vermont*, 26 HYDROLOGICAL SCI. BULL. 402, 405–06 (1981).

channels. Mountain streams are generally "flashy," a term hydrologists use to denote a rapid response to precipitation, a relatively sharp peak, and a quick return to base flow.[28] Small streams tend to be flashy in general, simply because water does not have far to travel and most of it arrives at the stream channel quickly. In flatter terrain, however, water follows a myriad of subsurface flow paths, tending to broaden hydrograph peaks, releasing water to the stream at different times.[29] The deep soils at low elevations provide significant water storage and release this water slowly to streams, sustaining base flow during low-flow times of year.[30] Thus, compared to lowlands, mountain streamflow generally has higher variability. These high-flow episodes are the important channel-forming events.[31] This is why mountain stream channels often appear oversized, with a trickle of water in a voluminous channel; but at different times of the year that channel must accommodate the occasional "gullywasher."

Subsurface hydrology may be less important in the mountain environment compared to the adjacent lowlands, but a grasp of the basics is important to understand the mountain stream. Rain and snowmelt infiltrate the soil and move both vertically and laterally downslope.[32] The underlying bedrock surface often forms a barrier to the downward movement of this water, creating a zone of saturation, called groundwater.[33] In saturated soils, water moves more rapidly downslope.[34] On steep mountain slopes, this saturated groundwater layer may be transient, dissipating nearly as quickly as it forms, but nonetheless providing a means of rapid downslope water transit through the soil. Groundwater tends to persist in flatter areas, particularly along stream channels, where it is important in sustaining streamflow between storms.

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[28] BLACK, *supra* note 2, at 239–40. Base flow is the flow in a stream arising from groundwater seeps alone, excluding surface runoff into the stream. WYMAN & STEVENSON, *supra* note 12, at 37.

[29] BLACK, *supra* note 2, at 240. A hydrograph is a graph of a stream or river discharge over time. WYMAN & STEVENSON, *supra* note 12, at 187. Therefore, when terrain is more level, water entering a stream tends to arrive at different times from different sources, causing the hydrograph to exhibit much broader peaks.

[30] *See* DUNNE & LEOPOLD, *supra* note 3, at 262–72 (describing how water infiltrates soil, which eventually becomes saturated, causing water to emerge from the ground downslope).

[31] LEOPOLD, *supra* note 1, at 126–31.

[32] DUNNE & LEOPOLD, *supra* note 3, at 262–72.

[33] *Id.* at 192–93.

[34] *Id.* at 179–80. Groundwater movement is expressed by Darcy's Law, an equation that relates groundwater velocity to the product of the permeability of the aquifer and the slope of the water table. *Id.* at 204.

Above the groundwater, or saturated zone, is the unsaturated zone of the soil, through which water moves more slowly.[35] In summer, this movement is not fast enough to escape thirsty tree roots, which make the unsaturated zone become increasingly dry. The rewetting of this zone, which occurs as vegetative demand for water drops off at the end of the growing season, is a key factor in increased streamflow in the fall. As soil moisture increases, groundwater levels rise to the land surface in stream channel areas. Rain or snowmelt on these now saturated areas then flows directly to the stream channel. The soil is analogous to a sponge: in the summer it is dried out and can absorb most of the water applied. In late fall and early spring, the soil is nearly saturated, causing additional water to run off immediately to streamflow. In the mountains this sponge is smaller, yet subjected to greater water input than in the adjacent lowlands, thus the tendency for high runoff in mountain streams.

Bedrock is not always a barrier to flow. Some rocks, such as sandstone and limestone, have intrinsic permeability—pore space within the rock through which water can move.[36] Other rocks may lack intrinsic permeability, but may be fractured.[37] Water entering bedrock fractures on a mountain slope may follow those fractures all the way to the valley below and bypass the mountain stream network altogether. Abbott, Lini, and Bierman found evidence of this occurring on the west slope of Mt. Mansfield in Vermont.[38] Alternatively, water entering fractures on one side of a mountain may issue from a fracture on the other side, or more commonly on the same side. Gains or losses of water from mountain streams that result from flow through bedrock fractures are generally minor, but may be important in some settings.

Snow—its accumulation in the snowpack and subsequent release in melting—plays an important role in streamflow in many mountain environments. Up to one-third of the annual precipitation in the northeastern United States and eastern Canada is stored in the mountain

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[35] DUNNE & LEOPOLD, *supra* note 3, at 194. A saturated zone is the zone in the earth's crust extending from the water table downward, in which pore spaces in the soil or rock are filled with water at greater than atmospheric pressure. WYMAN & STEVENSON, *supra* note 12, at 338. Conversely, the unsaturated zone consists of the upper layers of soil in which pore spaces in soil or rock are filled with water and air at less than atmospheric pressure. DUNNE & LEOPOLD, *supra* note 3, at 194. This zone is also called the zone of aeration.

[36] DUNNE & LEOPOLD, *supra* note 3, at 206 (showing table of values of permeability for geologic materials).

[37] *See id.* at 215 ("Fracture zones may provide valuable locations in rocks that otherwise provide relatively poor opportunities for groundwater development.").

[38] *See generally*, M.D. Abbott et al., *δ18O, δD, 3H Measurements Constrain Groundwater Recharge Patterns in an Upland Fractured Bedrock Aquifer, Vermont, USA*, 228 J. HYDROLOGY 101–12 (2000).

snowpack.[39] The snowpack depth and stored water content increases as elevation increases because of greater precipitation, higher percentage of snow relative to rain, and colder temperatures that limit melting.[40] In the spring, snowmelt releases this stored precipitation relatively quickly, causing about one-half of the total annual streamflow during just six weeks of snowmelt.[41] In the more alpine mountains of western North America, Europe, and elsewhere, snow and snowmelt dominate streamflow to an even greater extent. Nearly all of the annual flow in these areas is derived from snowmelt, thus peak flow may not occur in some locations until mid-summer.

Considerable energy is required to melt snow.[42] This energy may be supplied by various sources, including incoming shortwave solar radiation[43] longwave radiation,[44] advected energy from rain[45] and the latent heat of vaporization.[46] Short-wave radiation is generally the most important energy source, but under the right conditions latent heat can provide even more energy. The energy that latent heat produces can be observed in the formation of fog-condensed vapor droplets over the snowpack. Because of the high energy requirements, it is difficult to generate high streamflow rates by snowmelt alone; a high snow melt rate is equivalent to a light to moderate rainfall rate. When rainfall is added to a melting snowpack, however, the potential for very high streamflow peaks develops, especially when significant melt is occurring from latent heat.[47]

Before the snowpack can melt, it must ripen.[48] First, energy must be supplied to warm the entire snowpack up to zero degrees Celsius (Thirty-two degrees Farenheit).[49] Additional energy begins to melt the snow, but the remaining snowpack absorbs the meltwater in its pore space until it

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[39] *Id.* at 465.

[40] *See id.* at 466 (describing the parameters affecting snow cover and snow measurements).

[41] *See* LIKENS & BORMANN, *supra* note 9, at 48 ("[D]uring the spring snowmelt, stream water is composed of nearly pure snowmelt water.").

[42] *See* DUNNE & LEOPOLD, *supra* note 3, at 470 ("To melt one gram of ice at 0 degrees Celsius, 80 calories of heat must be transferred to the snowpack.").

[43] *Id.* at 471–72. Shortwave radiation is part of the range of wavelengths of energy emitted by the sun, including ultraviolet, visible, and near infrared radiation. WYMAN & STEVENSON, *supra* note 12, at 349.

[44] DUNNE & LEOPOLD, *supra* note 3, at 472–74. Longwave radiation is solar energy re-radiated by clouds, trees, and other objects. *See id.*

[45] Advection is transport by moving liquid or gas. WYMAN & STEVENSON, *supra* note 12, at 8.

[46] Latent heat of vaporization is the energy released by condensing vapor as warm, moisture-laden air passes over the snowpack. DUNNE & LEOPOLD, *supra* note 3, at 475–76.

[47] R.D. Harr, *Some Characteristics and Consequences of Snowmelt During Rainfall in Western Oregon*, 53 J. HYDROLOGY 277, 281–82 (1981).

[48] DUNNE & LEOPOLD, *supra* note 3, at 470–71.

[49] *Id.* at 471.

attains a critical level. At this point the snowpack is said to be ripe, and only after this point will further energy inputs cause meltwater to leave the snowpack (the sponge analogy applies here as well).[50] Two factors conspire to accelerate the snowmelt process once it begins. First, the aging snowpack becomes less reflective due to crystals changing form, and the emergence of organic debris within the pack as it melts down. The decreased reflectivity, or albedo, causes more of the shortwave radiation to be absorbed by the snowpack.[51] Secondly, as patches of bare ground and ablation rings around trees open up, these areas generate increased longwave radiation that is absorbed by the adjacent snowpack.[52]

Despite the large volume of streamflow generated by snowmelt, it may not always produce the highest peak flow of the year. The snowmelt peak is broad, and high flow is sustained over several weeks. The gradual snowmelt rate, even when combined with a moderate rainfall, typically cannot match the rainfall intensity that often accompanies summer convective storms. Soil moisture conditions, however, greatly influence the stream response. Summer storms usually occur on dry soils which absorb much of the rain, whereas the long gradual snowmelt process, occuring during the dormant season, creates wet soils, high groundwater levels, and expanded areas of surface saturation that rapidly shed subsequent rain and meltwater to the stream.

II. WATER QUALITY IN MOUNTAIN STREAMS

To many people, the image of a mountain stream is one of clean water, cascading over rocks and through a forest. For the most part this image is realistic. In most settings the mountain stream rises from rain or snowmelt that has filtered through forest soils. Apart from atmospheric contaminants in the precipitation or accumulated in the soils,[53] there is little to degrade the water quality. Extreme rainfall can erode steep slopes and clog streams with sediment, but under natural conditions stream channels have adapted to all but the most extreme events and sedimentation is usually minimal.

Streamwater is never free of impurities. There are two general classes of substances carried by water—dissolved constituents and particulate

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[50] *Id.* at 470–79.

[51] *Id.* at 472.

[52] J.P. Hardy et al., *Snow Ablation Modeling at the Stand Scale in a Boreal Jack Pine Forest*, 102 J. GEOPHYSICAL RES. 29397, 29403–04 (1997).

[53] Atmospheric deposition places solids and/or liquids from the atmosphere into mountain streams. "Snow, rain and dust are natural examples, whereas, acids, metallic dust, rock dust, and toxic organic compounds are deposits caused by human activities." WYMAN & STEVENSON, *supra* note 12, at 29.

matter.[54] Dissolved substances consist of both inorganic and organic solutes.[55] Inorganic solutes, such as calcium and sulfate, may either be deposited from the atmosphere or derived from the weathering (i.e. slow chemical breakdown) of minerals in the soils and rocks.[56] Decomposing organic matter, such as leaves and wood, releases both dissolved organic and inorganic material.[57] Dissolved organic matter often exhibits a yellow or brown color in natural waters. Particulate matter carried by streams consists of soil particles and organic debris.[58] Some substances, such as lead and phosphorous, have a strong chemical affinity for these particles and will only be present in significant amounts when particles are moving.[59]

Mountain streams generally have low concentrations of dissolved substances. Concentrations tend to increase downstream as water has more time to react with soil particles and dissolve soil minerals. The forest exerts an important influence on stream chemistry through its nutritional requirements.[60] For example, uptake of nitrate and phosphate by trees limits the concentrations of these ions in streamwater.[61] Because it involves both geologic and ecosystemic considerations, the study of the movement of chemical substances in forested ecosystems is known as "biogeochemistry."[62] Pioneering work in biogeochemistry began in the 1960's and continues today at Hubbard Brook Experimental Forest in New Hampshire.[63]

Hydrologic events, or high-flow periods, are an important aspect of mountain stream water quality. The rain or snowmelt causing a high-flow event is typically high quality water that is low in dissolved material. As streamflow increases from inputs of this dilute, high quality water, concentrations of major solutes such as calcium, chloride, and sulfate generally decrease. Unfortunately from the water quality perspective, many contaminants are associated with the organic-rich forest floor, or topsoil. These contaminants, which may include phosphate, metals such as lead and

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[54] DUNNE & LEOPOLD, *supra* note 3, at 5–6, 728.

[55] *Id.* at 727–33, 739–50. A solute is a substance dissolved in a solution, WYMAN & STEVENSON, *supra* note 12, at 358, in this case stream water.

[56] DUNNE & LEOPOLD, *supra* note 3, at 728–29.

[57] *Id.* at 728.

[58] *See* H.B.N. HYNES, THE ECOLOGY OF RUNNING WATERS 49 (1970) ("All natural surface waters contain dissolved and particulate organic matter . . . .").

[59] DUNNE & LEOPOLD, *supra* note 3, at 735. The absorption of lead, phosphorous and other substances by particulate matter, such as soil particles, is part of a chemical process known as ion exchange. WYMAN & STEVENSON, *supra* note 12, at 64.

[60] LIKENS & BORMANN, *supra* note 9, at 3.

[61] *Id.* at 2–4.

[62] *Id.* at 1–2.

[63] *Id.* at 122.

mercury, and pesticides, often increase in concentration during high-flow events as ground water levels rise and stormwaters pass through these organic soils on the way to the stream.

One of the primary water quality concerns during high-flow events is sediment mobilization. Sediment moved by streams is classified either as suspended sediment or bedload.[64] Suspended sediment is carried along with the water.[65] Concentrations of suspended sediments are generally very low or negligible at low flow, but may increase dramatically at high flow. Sediment begins to move at a certain flow threshold which is dependent on the grain size, and requires a certain flow velocity to keep it in suspension.[66] Sources of sediment may include upland areas (especially where the land surface has been disturbed), the near-stream zone, the stream banks, or the channel itself. Sediment may be deposited and resuspended repeatedly as stream velocities adjust to the pools and riffles of a mountain stream.[67] Bedload consists of cobbles and boulders generally too heavy to be suspended, but which are mobilized by very high flows and skirt along the channel bottom.[68]

The hallmark of high water quality in a stream is a healthy macroinvertebrate population. Macroinvertebrates, commonly the larval stage of flying insects, live in the sand and gravel beds of flowing streams.[69] Macroinvertebrates should thrive if there is adequate oxygen, no adverse chemical or temperature stresses, and no excessive sedimentation in the stream channel.[70] Many states, including Vermont, assess the macroinvertebrate population as a barometer of stream quality.[71] Certain species begin to disappear as stream quality degrades, and tracking the various populations gives an indication of status and trends. Sediment deposition, in particular, degrades macroinvertebrate habitat by filling in the spaces in the sand and gravel with finer sediments,[72] creating a condition known as

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[64] LUNA B. LEOPOLD ET AL., FLUVIAL PROCESSES IN GEOMORPHOLOGY 180 (1964).

[65] *Id.* at 180–81.

[66] *Id.* at 176–77.

[67] *See supra* note 1 and accompanying text.

[68] LEOPOLD ET AL., *supra* note 64, at 180.

[69] HYNES, *supra* note 58, at 112–15.

[70] *Id.* at 196–222.

[71] U.S. Environmental Protection Agency, *Invertebrates as Indicators*, *at* http://www.epa.gov/bioindicators/html/invertebrate.html (last visited Feb. 18. 2002); Water Quality Division, Vermont Department of Environmental Conservation, *Why Biomonitoring?*, *at* http://www.vtwaterquality.org/bassabn.htm (last visited Jan. 16, 2002). The macroinvertebrate population is seen as an "indicator" population, or a population whose characteristics show the presence of specific environmental conditions or contamination. *See generally* John Cairns, Jr. & James R. Pratt, *A History of Biological Monitoring Using Benthic Macroinvertebrates*, *in* FRESHWATER BIOMONITORING AND BENTHIC MACROINVERTEBRATES 10, (David M. Rosenberg & Vincent H. Resh, eds.) (1992).

[72] GILLER & MALMQVIST, *supra* note 1, at 242.

embeddedness.[73] Macroinvertebrates are the primary food supply for small fish; thus, a healthy macroinvertebrate population is vital to a healthy fish population.

Two critical factors in stream health are dissolved oxygen concentration and stream temperature. In addition, these factors affect a stream's fish populations and plant life. Dissolved oxygen is usually maximized in a mountain stream as the cascading waters incorporate air and continually renew any oxygen that the stream fauna or respiring flora and heterotrophs consume.[74] Trout require cool temperatures in summer, and this condition is generally met in forest ecosystems of cold mountain regions. A later Part of this Paper discusses the ways in which development may potentially degrade water quality and fish habitat.[75]

III. POTENTIAL EFFECTS OF MOUNTAIN DEVELOPMENT ON HYDROLOGY: WHAT HAPPENS TO A MOUNTAIN STREAM WHEN A RESORT IS DEVELOPED AROUND IT?

As mentioned above, there has been little study of the hydrologic effects of development at mountain resorts.[76] Thus, when determining effects of resorts one must rely on information learned from forest clearing and urbanization studies, and infer how these results might transfer to the ski resort setting. The lack of study in eastern North America is particularly notable. While some studies have been made at western and overseas ski resorts, they require extrapolation to apply to the landscape of New York, New England, and Québec. This Part addresses the effects of development on water flow in streams. Succeeding Parts take up the special case of snowmaking, the effects of development on water quality, and finally a short discussion section on the question of transferability of these studies to the mountain resort setting.

In general, removal of a significant amount of the forest cover causes an increase in streamflow.[77] Land development, which leads to compacted soils and impervious surfaces such as roads and roofs, has a similar effect.[78] Tree clearing allows more of the precipitation to reach the ground, and the lack of vegetative demand makes more water available to run off to

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[73] *Id.* at 40.

[74] HYNES, *supra* note 58, at 40.

[75] *See infra*, Part V.

[76] Aside from those studies required by regulatory agencies when resorts apply for development permits, etc.

[77] DUNNE & LEOPOLD, *supra* note 3, at 152.

[78] DUNNE & LEOPOLD, *supra* note 3, at 275.

streams.[79] Removal of trees may also result in increased snow accumulation in high-elevation environments, leading to increased runoff during melt or rain-on-snow events.[80] Impervious surfaces allow precipitation to run off directly to streams rather than slowly percolate through the soil.[81] The net result of these conditions is a tendency for higher and earlier peak flows and greater water yields from cleared landscapes than from standing forests [Figure 2].[82]

The classic experimental approach to quantify the effects of forest clearing on water runoff is the paired watershed study. In this approach, researchers select two watersheds with similar characteristics. Theoretically, if the watersheds are near each other and have similar size, soils, slopes, elevation, aspect, and forest cover, they should have similar hydrology. Flow is measured at both sites—preferably for several years, to quantify natural differences in the hydrology.[83] One basin is then harvested. The difference in flow in the two basins is corrected for any natural differences determined during the pre-treatment period; any remaining difference is ascribed to the harvest. These measurements are also continued for many years to observe the initial effect and the recovery. Simultaneous water quality monitoring can likewise determine the effects on water quality.

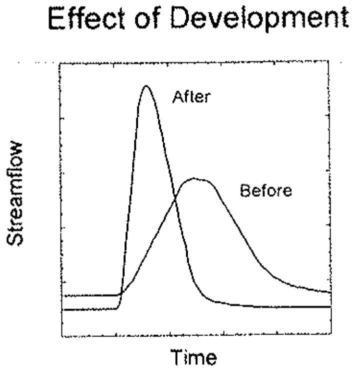

Figure 2. Theoretical shift in storm hydrograph to earlier and higher peak flows as a result of land disturbance and/or development.

Bosch and Hewlett reviewed nearly one hundred paired catchment studies.[84] The collective results indicated that forest clearing increases water yield, due to the reduction in evapotranspiration.[85] For example, at Hubbard Brook, New Hampshire, Hornbeck and others found a three

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[79] J.A. Jones, *Hydrologic Processes and Peak Discharge to Forest Removal, Regrowth, and Roads in Ten Small Experimental Basins, Western Cascades, Oregon*, 36 WATER RES. RESEARCH 2621, 2622 (2000).

[80] Harr, *supra* note 47, at 296–300.

[81] Jones, *supra* note 79, at 2623.

[82] BLACK, *supra* note 2, at 124. *See generally* I.R. Calder, *Hydrologic Effects of Land Use Change*, *in* HANDBOOK OF HYDROLOGY 1–99 (D.R. Maidment, ed., 1993).

[83] *See supra* Part I. for a general explanation of the influences on hydrology.

[84] J.M. Bosch & J.D. Hewlett, *A Review of Catchment Experiments to Determine the Effect of Vegetation Changes on Water Yield and Evapotranspiration*, 55 J. HYDROLOGY 3, 3 (1982).

[85] *Id.* at 4.

hundred and ten millimeter per year increase in flow in the first two years after clearcutting.[86] In a wider regional analysis of eleven paired catchment studies in the northeastern United States, Hornbeck and his colleagues found initial water yield increases of as much as three hundred and fifty millimeters per year where regrowth was suppressed, and from one hundred and ten to two hundred and fifty millimeters per year where regrowth was allowed.[87] As the forest grew back, the excess water yield diminished relatively quickly and disappeared in ten years.[88] Most of the flow increase occurred in the dry summer months.[89] In ten Oregon catchments, Jones also found the largest flow increase during the dry season.[90] Hewlett and Helvey, working at the Coweeta watershed in western North Carolina, found eleven percent greater stormflow volume, seven percent higher peaks, but no change in peak flow timing after clearcutting.[91] They likewise attributed the increased water yield to reduced evapotranspiration.[92] Troendle and King found that flow increases persisted thirty years after partial cutting in the semi-arid Colorado Rockies.[93]

The effects of forest roads on hydrology are related to the effects of forest clearing. Most logging requires road access, and the roads often remain after the logging, so there are both short and long-term effects.[94] Forest road surfaces are relatively impermeable. Water readily runs over the road surface and associated roadside ditches, often directly to a stream channel, with the net effect of extending channel networks and increasing drainage density.[95] In addition to providing conduits for overland flow, forest roads involve slope-cuts and ditching that may intersect the water table and interrupt natural subsurface water movement.[96] This diversion of subsurface water may be quantitatively more important than the overland flow of stormwater in some watersheds.[97] The importance of roads in

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[86] J.W. Hornbeck et al., *Streamflow Changes After Forest Clearing in New England*, 6 WATER RES. RESEARCH 1124, 1126 (1970).

[87] J.W. Hornbeck et al., *Long-Term Impacts of Forest Treatments on Water Yield: A Summary for Northeastern USA*, 150 J. HYDROLOGY 323, 323 (1993).

[88] *Id.* at 337–38.

[89] *Id.* at 330.

[90] Jones, *supra* note 79, at 2635.

[91] J.W. Hewlett & J.D. Helvey, *Effects of Forest Clear-felling on the Storm Hydrograph*, 6 WATER RES. RESEARCH 768, 774–75 (1970).

[92] *Id* at 778.

[93] C.A. Troendle & R.M. King, *The Effect of Timber Harvest on the Fool Creek Watershed, 30 Years Later*, 21 WATER RES. RESEARCH 1915, 1915 (1985).

[94] *See generally* Beverly C. Wemple et al., *Channel Network Extension by Logging Roads in Two Basins, Western Cascades Oregon*, 32 WATER RESOURCES BULL. 1195 (1996).

[95] *Id.* at 1201–02.

[96] Beverly C. Wemple, Investigations of Runoff Production and Sedimentation on Forest Roads 168 (1998) (unpublished Ph.D. dissertation, Oregon State University) (on file with author).

[97] *Id.*

altering basin hydrology has been underscored in paired-watershed studies and recent modeling studies.[98]

Only one scientific study specifically addresses the hydrologic or water quality effects from ski areas in New England.[99] Hornbeck and Stuart did not have the benefit of direct data from a ski area; instead, they extrapolated from results of a strip cutting study at Hubbard Brook, New Hampshire, to simulate ski trail clearing.[100] They found that at Hubbard Brook, where one-third of the trees were removed, runoff increased several centimeters per year, but mainly during the summer low-flow period.[101] They argued that this was not a concern, as an increase in low-flow did not tax the existing capacity of the stream channel.[102] They noted, however, that ski trail clearing involves considerably more disturbance, including soil removal and soil compaction, which may lead to impervious surfaces and potentially more runoff in the short term.[103] If care is taken, these problems can be minimized. Vigorous herbaceous growth on the trails can match the water demand of the original forest and thereby eliminate any effects on runoff once the ground cover is well established.[104]

Ski trails act as gaps in the canopy, with a high efficiency of precipitation capture. The simple presence of an opening in the forest is known to increase the effective precipitation. There are two reasons for this increase. First, rain or snow falling on the forest canopy is intercepted by leaf or needle surfaces and some of it evaporates back to the atmosphere, without ever reaching the ground.[105] Second, the reduced wind in forest clearings

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[98] *See, e.g.*, R.D. Harr et al., *Changes in Storm Hydrographs After Road Building and Clear Cutting in the Oregon Coast Range*, 11 WATER RES. RESEARCH 436 (1975); Jones, *supra* note 79, at 2638; J.G. King & L.C. Tennyson, *Alteration of Streamflow Characteristics Following Road Construction in North Central Idaho*, 20 WATER RES. RESEARCH 1159 (1984); J.L. LaMarche & D.P. Lettenmeier, *Effects of Forest Roads on Flood Flows in the Deschutes River, Washington*, 26 EARTH SURFACE PROCESSES & LAND FORMS 115 (2001); W.T. Swank et al., *Streamflow Changes Associated With Forest Cutting, Species Conversions and Natural Disturbances*, *in* 66 FOREST HYDROLOGY AND ECOLOGY AT COWEETA 297, 312 (W.T. Swank et al. eds., 1988) (finding that carefully located and designed forest roads only increase mean streamflow volumes and peak flow rates by approximately 15 percent); Christina Tague & Larry Band, *Simulating the Impact of Road Construction and Forest Harvest on Hydrologic Response*, 26 EARTH SURFACE PROCESS & LAND FORMS 135, 149 (2001).

[99] S. Hornbeck & G. Stuart, *When Ski Trails Are Cut Through Forestland, What Happens to Streamflow?*, SKI AREA MGMT. 34 (1976).

[100] *Id.* at 34.

[101] *Id.* at 35.

[102] *Id.* at 36.

[103] *Id.* at 35.

[104] *Id.* at 36.

[105] DINGMAN, *supra* note 8, at 399–413; DUNNE & LEOPOLD, *supra* note 3, at 152.

favors increased deposition of snow.[106] The latter effect has spurred efforts to increase snowpacks by strategic forest clearing in western North America.[107]

Ski trails, like forest roads, frequently involve slope cutting and grading, and once created, the trails are designed to be a permanent feature on the landscape.[108] Ski trails are more pervious than forest roads, but their infiltration capacity is frequently lessened by compaction and soil disturbance. As with roads, erosion is undesirable, and ski trails have ditches and water bars to lead water away. Some ski areas have toll roads to their summits for tourist use,[109] and most ski areas have one or more service roads leading up the mountains for maintenance vehicles in summer and snow grooming equipment in winter. Often doubling as ski trails, the roads are more likely than ski trails to have side cuts and ditching as they switchback up the mountain. Roads are also likely to have a more compacted surface capable of generating overland flow than standard ski trails.

Several competing factors affect the timing and quantity of runoff from ski trails. In theory, the studies discussed above suggest that ski trails would receive more snow than adjacent forested areas. Moreover, increased solar radiation in forest openings would tend to increase snowmelt rates. In the New Hampshire strip cut experiment, Hornbeck and Stuart found that the cleared strips melted four to eight days sooner than the adjacent forest.[110] Further, ski trails and service roads delivered rain and snowmelt more efficiently to stream channels than adjacent permeable forest soils. On the other hand, compaction of snow on ski trails by skiers and by trail grooming activity may have offsetting effects, causing snow to melt more slowly and delaying runoff.[111] In addition, machine-made snow is intrinsically more dense and also tends to melt more slowly.[112] For example, at a ski area in New Hampshire, complete snowpack loss occurred nineteen days later on slopes with snowmaking than without snow-

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[106] H.G. Wilm & E.G. Dunford, Effect of Timber Cutting on Water Available for Streamflow From a Lodgepole Pine Forest, USDA Tech. Bull. 968 (1948); Hornbeck et al., *supra* note 87; Troendle & King, *supra* note 93, at 1917.

[107] *See generally* C.A. Troendle & J.R. Meiman, *Options for Harvesting Timber to Control Snowpack Accumulations*, 52 PROC. WESTERN SNOW CONF. 86 (1984).

[108] Hornbeck & Stuart, *supra* note 99, at 36.

[109] For example, Stowe Mountain Resort on Mount Mansfield allows visitors to travel near to the summit by way of a toll road.

[110] Hornbeck & Stuart, *supra* note 99, at 35.

[111] Kathleen S. Fallon & Paul K. Barten, A Study of the Natural and Artificial Snowpacks at a New Hampshire Ski Area 8–10 (1992) (unpublished M.F.S research project, Yale School of Forestry and Environmental Studies) (on file with author).

[112] *Id.* at 9.

making.[113] Similarly, at a ski area in Montana, snow compaction delayed snowmelt runoff for seven to fourteen days.[114] In contrast, Chase's study found that there was little difference in the timing of runoff in streams draining a ski area and an adjacent watershed in Maine, though runoff amounts were not measured.[115] He attributed the synchronous melt to offsetting factors that enhance or delay snowmelt in compacted snowpacks.[116] Because of these potentially offsetting effects, it is difficult to predict the timing and magnitude of the spring runoff in watersheds where alpine ski trails make up most of the forest openings.[117]

The mountain environment presents additional complexities that influence water quantity. Some mountains receive a significant percentage of their precipitation as cloud water interception.[118] The effectiveness of cloud water interception decreases sharply when trees are removed.[119] In the Cascade Range in Oregon, loss of cloudwater interception balanced the decrease in evapotranspiration after logging at two catchments.[120] Another influence on water quality is topographic complexity in the mountain environment, which affects the capture and redistribution of snow. In a mountain watershed in southwestern Idaho, the snow water equivalent varied substantially among various topographic settings that represented zones of snow accumulation or depletion through drifting.[121] High winds in an alpine environment may also affect water quantity, but little is known about the effectiveness of snow capture on ski trails that tend to be aligned along steep vertical gradients with openings at either end that may serve as "wind corridors." In the windy alpine environment, the "lay of the land" relative to prevailing winds may outweigh forest opening patterns in dictating snow deposition; snow is scoured from the windward side and deposits on the leeward side. Tuckerman's Ravine in New Hampshire provides a classic example of this phenomenon. Snow from windswept Mt.

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[113] *Id.* at 10.

[114] Thomas R. Grady et al., The Effects of Snow Compaction on Water Release and Sediment Yield, Bridger Bowl Ski Area Gallatin County, Montana, Montana University Water Resources Center Report No. 124, at 9 (1982).

[115] James E. Chase, The Physical Characteristics and Meltwater Output from a Show Cover Compacted By Ski-Area Operations 60 (1997) (unpublished M.Sc. Thesis, University of New Hampshire) (on file with author).

[116] *Id.* at 77.

[117] Karl W. Birkeland, *The Effect of Ski Run Cutting and Artificial Snowmaking on Snow Water Accumulation at Big Sky Area, Montana*, PROC. WESTERN SNOW CONF. 137, 146 (1996).

[118] BLACK, *supra* note 2, at 100–01.

[119] Jones, *supra* note 79, at 2623.

[120] *Id.* at 2622–23.

[121] D. Marks et al., *Simulating Snowmelt Processes During Rain-on-Snow over a Semi-Arid Mountain Basin*, 32 ANNALS GLACIOLOGY 195 (2001).

Washington accumulates to great depth in the ravine and may remain until late summer.[122]

A final aspect of hydrological effects to consider is stream water extractions. The mountain resort usually turns to its own streams and/or ponds to supply its operational water needs.[123] Much of this water demand comes during winter and summer periods of the year, when supply is most limited.[124] Snowmaking is the most publicized water demand and will be discussed in the next Part. Increasingly, mountain resorts are becoming four-season facilities and water demands are becoming year-round as well.[125] Water use for residential and resort facilities may be small compared to demand for snowmaking in winter, but summer water use is on the rise for landscaping, swimming pools, and in particular, golf courses.[126] During the summer low-flow period these demands can tax small mountain streams.[127]

Although the mountain environment is the primary focus of this Paper, it is important to keep in mind that events in the mountains have repercussions downstream. The mountain environment is the headwater environment. Perturbations to the hydrologic cycle in the mountains are transmitted to the landscape downstream, whether it be increased flood peaks, increased frequency of high-flow events, or excessive winter water withdrawals. The environment downstream of a ski resort is often a resort village or valley, which may have development issues of its own. Flood peaks that may be enhanced by mountain development could cause or exacerbate flooding in mountain valleys.[128]

IV. SNOWMAKING

Machine-made snow has unique effects on the hydrology of mountain streams. The earliest attempts at snowmaking were in the late 1940's, and

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[122] *See* LAURA WATERMAN & GUY WATERMAN, FOREST & CRAG (1989) (discussing conditions on Mt. Washington); *see also Tuckerman Ravine*, *at* http://www.tuckerman.org/tuckerman/tuckerman.htm (last visited Apr. 16, 2002) ("This large glacial cirque, with its bowl-like form, collects snow blowing off the Presidential Range. Snow averages 55 feet in the deepest spot . . . .").

[123] OnTheSnow.com, *It's Our Turn*, Jan. 4, 2002, *at* http://www.onthesnow.com (no longer available, copy on file with author).

[124] *Id.* ("Killington . . . used to consume so much water from Roaring Brook that the stream would dry to a trickle.").

[125] *See* J. Pelley, *States Combat Ski Resort Pollution*, 35 J. ENVTL. SCI. & TECH. 60 A (2001) (discussing the expansion of ski resorts to encompass condominiums, golf courses, and second homes).

[126] *Id.*

[127] *See id.*

[128] For an overview of secondary development issues, see Jonathan Isham & Jeff Polubinski, *Killington Mountain Resort: A Case Study of 'Green' Expansion in Vermont*, 26 VT. L. REV. 565 (2002).

the practice became common by the 1960's as a means to ensure snow cover for an increasingly popular ski industry. Improvements and efficiencies were continually realized as the art of snowmaking spread. Even resorts located in usually reliable snow areas like the Rocky Mountains and the Alps now employ some snowmaking, but in eastern North America it is a mainstay of the business.[129] Snowmaking starts in October or November to allow early season skiing and ensure good snow conditions during the December holiday period. In February, snowmaking activity usually drops off, but the accumulated snow allows the ski season to extend well into April and sometimes May or June.[130]

Machine-made snow is produced when compressed air is introduced to a stream of pumped water, breaking the water into fine droplets and forcibly ejecting it through a nozzle.[131] The fine mist of water droplets readily freezes into fine, dense crystals.[132] Because water needs a nucleus to induce the formation of ice crystals, early snowmaking relied on impurities in the water or air, or existing ice crystals to serve as the nucleus.[133] Snowmakers have found they can increase the efficiency of the process, and make snow at higher temperatures (up to minus zero point five degrees centigrade, or thirty-one degrees Fahrenheit) by adding nucleating material to the water at the source.[134] Commonly, the nucleating material is a protein isolated from cultured bacteria. The structure of the protein offers a high density of nucleation sites.[135]

A. *Snowmaking in Eastern North America*

Snowmaking has become such an integral part of ski resort operations in eastern North America that the water source for snowmaking is often at the heart of ski resort development or expansion plans. The water source is generally at the bottom of the mountain, so considerable pumping capacity is required. Typically, the streams at the base of mountain developments are too small to serve this demand easily, yet the cost of pumping water

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[129] *See* Vermont Ski Area Association, *Vermont Snowmaking Facts*, *at* http://www.skivermont.com/environment/Snowmkg.html (last visited Apr. 16, 2002).

[130] *See, e.g.*, Killington, Ltd., *Killington has the longest season in eastern North America*, *at* http://www.killington.com (last visited Sept. 12, 2002).

[131] Laurie Lynn Fischer, *There's No Business Like Snow Business*, RUTLAND HERALD, Jan. 8, 2001.

[132] GoSki.com & American Skiing Company, *Everything You Ever Wanted to Know About Snowmaking*, *at* http://www.goski.com/news/snowmake.htm (last visited Apr. 1, 2002).

[133] York Snow, Inc., *The Science of Making Snow*, *at* http://www.snowmax.com/education/index.htm (last visited Apr. 16, 2002).

[134] *Id.*

[135] *Id.*

from a larger source down-valley is at times prohibitive.[136] One of the primary concerns in snowmaking water withdrawals is maintaining sufficient flow to protect overwintering fish eggs and macroinvertebrates. Some fish, including trout, spawn in the fall and deposit their eggs in gravel stream bottoms.[137] If flows become too low, the eggs are at risk of freezing. Most states, including Vermont, make new development or expansion contingent upon maintaining a minimum streamflow, typically the February Median Flow (FMF).[138] Flow generally reaches its lowest winter level in February, so it is thought that fish habitat and spawning grounds are adapted to these low levels.[139] Snowmaking is prohibited if flow falls below the FMF.[140]

To help meet snowmaking water demands from small mountain streams, ski areas commonly construct storage reservoirs to make the most of any available water (flow in excess of the FMF).[141] For example, a reservoir filling all day may provide enough water to make snow during the night hours. Siting of storage reservoirs can be a problematic issue in ski area permitting[142] due to aesthetic considerations, the need to avoid wetlands or the stream corridor itself, and the scarcity of suitably flat terrain away from the channel.[143] Storage reservoirs also may contribute to water quality problems, an issue addressed in the next Part.[144] Where economically practical, water for snowmaking may be pumped from a reservoir outside the basin. This interbasin transfer of water increases the overall amount of water the mountain stream system must convey.

Intuitively, removing water from a stream and redepositing it as snow back up the mountain will delay the timing and increase the magnitude of

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[136] *See* OnTheSnow.com, *Daily New England News*, Jan. 4, 2002, *at* http://www.onthesnow.com. ("Nearly two decades of battling over snowmaking and land development eventually lead to a $5 million solution. The resort [Killington] completed construction of a 1.8 mile pipeline for snowmaking water in Sept. 2000.") (no longer available, copy on file with author).

[137] COLBERT E. CUSHING & J. DAVID ALLAN, STREAMS: THEIR ECOLOGY & LIFE 69 (2001).

[138] Isham & Polubinski, *supra* note 128, at 571 n.48; *see also* Vermont Ski Area Association, *supra* note 129 ("The February median Flow (FMF) standard was adopted as part of the water withdrawal rules by the [Vermont] Legislature in 1996 and is the strictest in the nation.").

[139] Vermont Ski Area Association, *supra* note 129.

[140] *Id.* ("Vermont ski areas now either comply with FMF or must meet FMF when expanding snowmaking operation.").

[141] *See, e.g.*, Isham & Polubinski, *supra* note 128, at 572 (discussing Killington's use of Woodward Reservoir).

[142] *Id.*

[143] For an example of a legal struggle over the potential for such an effect, see *Killington, Ltd. v. State*, in which Killington challenged a ruling by the Vermont Environmental Board which denied an application to build a snowmaking pond in a fragile area. Killington, Ltd. v. State of Vermont and Town of Mendon, 164 Vt. 253, 668 A.2d 1278 (1995).

[144] *See infra* note 198 and accompanying text.

snowmelt runoff in spring. As noted in the previous Part, snow compaction from skier traffic delays snowmelt.[145] Unlike natural snow, machine-made snow is intrinsically dense, and thus tends to melt more slowly.[146] The greater depth and density of snow on the trail increases the time necessary for the snowpack to ripen, also delaying the onset of melt.[147] As spring progresses the melting snow receives increased solar radiation and melts more rapidly.[148] These rapid melt rates and large snow packs should lead to greater flow peaks. But, if ski trails comprise only about twenty percent of a watershed, and only some of the trails have snowmaking, is it enough to cause a discernable difference in peak flows? As mentioned, Chase found no difference in the timing of runoff, but he did not measure flow rates.[149] Apparently, there have been no definitive studies that address this question.[150]

B. Snowmaking in the Western United States

In western North America, snowmaking is less extensive than in the eastern regions, but water is also less abundant.[151] Water withdrawals are subject less to environmental regulations than to local water rights provisions. Water rights are needed only for consumptive use, i.e. water withdrawn from a stream and not returned.[152] To determine the consumptive loss from snowmaking, Colorado researchers performed two assessments.[153] The first study determined that about six percent consumptive loss occurred during the snowmaking process.[154] This initial loss represents water that left the snowmaking gun but evaporated or sublimated before reaching the ground.[155] The second study combined hydrologic modeling and measurements at six Colorado ski areas to determine that an additional seven to thirty-three percent consumptive loss occurred from the

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[145] *See supra* Part III.

[146] *Id.*

[147] Chase, *supra* note 115, at 80.

[148] Fallon & Barten, *supra* note 111, at 10.

[149] Chase, *supra* note 115, at 60.

[150] *See* Birkeland, *supra* note 117, at 146.

[151] For a general discussion of water issues in the western United States, see MARC REISNER, CADILLAC DESERT, THE AMERICAN WEST AND ITS DISAPPEARING WATER (1993).

[152] Leo M. Eisel et al., *Estimated Consumptive Loss From Man-Made Snow*, 24 WATER RESOURCES BULL., 815, 815 (1988) (finding that ski areas reduce the amount of water rights needed by calculating consumptive loss from snowmaking).

[153] *Id.*; Leo M. Eisel et al., *Estimated Runoff From Man-Made Snow*, 26 WATER RESOURCES BULL. 519, 519 (1990) (studying the consumptive loss that occurs to man-made snow particles while they reside in the snow pack until spring snowmelt).

[154] Eisel, *supra* note 152, at 818.

[155] *Id.* at 815.

watershed.[156] This watershed loss represents water that evaporated or sublimated from the snowpack or, as the snow remained into the growing season, was consumed by evapotranspiration.[157] In eastern North America, the humid climate and frequent rainfall limits all categories of these consumptive losses. Therefore, in the East, most of the water withdrawn from streams in the winter will add to runoff in the spring, increasing the potential for high spring flow peaks.

V. POTENTIAL EFFECTS OF DEVELOPMENT ON WATER QUALITY

As with hydrologic effects, there has been limited study of the water quality effects of mountain resorts. To estimate water quality effects, it is necessary to draw from the results of forest clearing and urbanization studies. Two types of water quality problems have been identified in forest removal studies: 1) sediment production in runoff over disturbed soils and forest roads, and 2) release of nutrients such as nitrate and calcium due to interruption of biological uptake.[158] Many studies have linked the soil disturbance associated with forest clearing to increased soil erosion and sediment loading to streams.[159] In extreme cases, poorly-managed forest clearing and road construction on steep slopes, followed by heavy rains, may result in landslides.[160] Direct runoff over impervious forest road surfaces is another mode of sediment movement.[161] Nutrient releases resulting from forest clearings are likely to have the greatest effect in downstream environments, but have only been considered briefly in this Part.[162] More attention will be given to direct water quality effects from the

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[156] Eisel, *supra* note 153, at 520, 525.

[157] *Id.* at 519.

[158] *See, e.g.*, MICHAEL LIDDLE, RECREATION ECOLOGY 82 (1997) (citing a 1974 study that found a significantly higher level of nitrogen and potassium in areas trampled by a pathway).

[159] ROY C. SIDLE ET AL., HILLSLOPE STABILITY AND LAND USE 9, 73–74 (1985).

[160] David R. Montgomery, *Road Surface Drainage, Channel Initiation, and Slope Instability*, 30 WATER RES. RESEARCH 1925, 1931–32 (1994); J. Sessions et al., *Road Location and Construction Practices: Effects of Landslide Frequency and Size in Oregon Coast Range*, 2 W. J. APPLIED FORESTRY 119, 121–22 (1987); F.J. Swanson & C.T. Dyrness, *Impact of Clear-Cutting and Road Construction on Soil Erosion by Landslides in the Western Cascade Range, Oregon*, 3 GEOLOGY 393, 394–95 (1975) (focusing on the H.J. Andrews experimental forest in the Western Cascade Mountains, and finding that roads contribute "about half of the total management impact" and that those impacts were most severe during the first few storms after the initial road construction).

[161] Leslie M. Reid & Thomas Dunne, *Sediment Production From Road Surfaces*, 20 WATER RES. RESEARCH 1753, 1753 (1984); A.D. Ziegler & T.W. Giambelluca, *Importance of Rural Roads as Source Areas for Runoff in Mountainous Areas of Northern Thailand*, 196 J. HYDROLOGY 204, 205–06 (1997).

[162] C. Wayne Martin et al., *Effects of Forest Clear-cutting in New England Stream Chemistry*, 13 J. ENVTL. QUALITY 204, 204–08 (1984); C. Wayne Martin & Robert S. Pierce, *Clear-Cutting Patterns Affect Nitrate and Calcium in Streams of New Hampshire*, 78 J. FORESTRY 268, 271–72 (May 1980).

resort facility and residential development, and roads and vehicles, which have an analog in urbanization effects.

Water quality degradation from mountain development is in essence a two-part problem—the adverse effect itself, and the limited means of the mountain environment to cope with the effect. An activity that may have little or no environmental effect in flat or gently sloping terrain may have a large effect in the mountains.[163] Mountains are sensitive environments because of the steep slopes, lack of thick soil cover, limited groundwater system, and climatically stressed vegetation.[164] When impervious surfaces are created, the steep slopes allow stormwater and snowmelt runoff to move quickly to streams.[165] Hydrology and water quality are interrelated, in that this runoff acquires contaminants which move along with it. Water quality problems from mountain development may include septic system leakage or failure, salt contamination from roadway de-icing, heavy metals and petroleum derivatives from vehicles, and contamination from fertilizers and pesticides, especially if the resort operates a golf course.[166] A common water quality problem at most ski resorts, however, is sediment transport and deposition.[167]

Some ski area managers feel that if they can solve their sediment problem, they have solved their water quality problem. This is mostly true, but why? What is so harmful about sediment? Regardless of whether sediment is deposited from erosion of disturbed surfaces within the watershed, or from the sloughing of stream banks as a channel adjusts to a new flow regime, the deposition negatively affects aquatic communities by degrading habitat on the stream substrate.[168] Fine sediments tend to settle in the slower-moving waters of stream pools, effectively clogging the gravel substrate, which provides refuge for macroinvertebrates and amphibians, and shelter for fish eggs after spawning.[169] One study clearly demonstrated the interrelationship among impervious surface, sediment concentrations, and species richness.[170] The study found that as the percentage of

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[163] *See supra*, Part I., describing hydrologic factors associated with mountain/high slope runoff.

[164] *See* MCKNIGHT, *supra* note 25, at 339 ("Where slopes are relatively steep, surface erosion progresses more rapidly, with the result that such soils are nearly always thin.").

[165] *See supra* Part I., describing general hydrologic processes.

[166] *See Pelley*, *supra* note 125, at 60 A.

[167] For an example of this problem see Project Proposal, Lelia Pascale, Marianne Muth Statement of Problem, *at* http://geology.uvm.edu/morphwww/classes/morph/2001/projects/proposals/leliamariane.pdf (last visited Apr. 16, 2002).

[168] *Id.*

[169] *See supra* note 1 and accompanying text, discussing pools and riffles in running streams.

[170] T.R. Scheuler, *Minimizing the Impact of Golf Courses on Streams*, 1(2) WATERSHED PROTECTION TECH. 73 (1994).

impervious surface in a watershed increases, species richness declines.[171] Further study of lowland environments has shown that increasing development of a watershed leads to degradation of fish habitat.[172]

Construction of resort facilities, ski trails, and service roads disturbs the land and creates the potential for sediment transport.[173] Sediment production can be minimized by implementing measures such as sediment fencing, water bars, ditching, and soil stabilization through vegetation.[174] Nonetheless, the steep slopes and frequent storms in the mountains make some erosion nearly unavoidable.[175] The potential for erosion is greatest immediately after disturbance. However, the creation of impervious or compacted surfaces allows more overland flow, and thus a greater potential for erosion, compared to the undeveloped landscape.

One method used to assess watershed disturbance and sedimentation potential is the Cumulative Watershed Effects (CWE) approach.[176] This approach is occasionally applied at ski areas, most notably in the Lake Tahoe region.[177] The CWE approach characterizes development activity within a watershed and gives each activity a relative rating of its potential to generate overland flow and sediment. For example, a given area of ski trail might be assigned one-half the effect of the same area of parking lot. The land area of each activity is weighted by its effect factor and they are all summed to yield an overall effects factor for the watershed. Certain threshold values of this factor are regarded as an upper limit of what a watershed can withstand, and are used as a guide for planning purposes. In an analysis of geomorphological changes in nine Vermont streams, researchers found this approach meaningful.[178]

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[171] *Id.* at 75.

[172] Amy L. Moscrip & David R. Montgomery, *Urbanization, Flood Frequency, and Salmon Abundance in Puget Low Streams*, 38 J. AMER. WATER RESOURCES ASSN. 1289, 1295 (1997).

[173] *See, e.g.*, *Re: Killington, Ltd.*, No. 1R0813-5, Findings of Fact and Conclusions of Law and Order (Vt. Dis. Env. Comm. #1, Aug. 25, 1997) (discussing concerns associated with mountain development).

[174] *See supra* note 7 and accompanying text.

[175] C.A. Troendle & W.K. Olsen, *Potential Effects of Timber Harvest and Water Management on Streamflow Dynamics and Sediment Transport*, USDA FOREST SERVICE GEN. TECHNICAL REP. RM-247, 34–41 (1993).

[176] Lee H. MacDonald, *Evaluating and Managing Cumulative Effects: Process and Constraints*, 26 ENVTL. MGMT. 299, 300–01 (2000).

[177] *See generally* John Cobourn, *An Application of Cumulative Watershed Effects Analysis on The Eldorado National Forests in California*, PROC. OF SYMPOSIUM ON HEADWATERS HYDROLOGY AMER. WATER RES. ASS'N 449 (1989); John Cobourn, *Using Cumulative Watershed Effects Analysis for Land Use Management in Ski Areas*, PROC. ANNUAL SUMMER SYMPOSIUM OF THE AMER. WATER RES. ASS'N 197 (1994).

[178] Memorandum from the Center for Watershed Protection, to Larry Becker, State Geologist, Vermont Agency of Natural Resources (Nov. 12, 2000) (on file with author).

Some researchers have studied erosion and sediment production at ski resorts. Ries studied erosion damage on ski trails in the Black Forest of Germany, a glaciated landscape with topography, elevations, and climate similar to the mountainous areas of New York and New England.[179] Grading and hollow filling during original trail and lift construction, combined with the action of trail grooming equipment and skis traversing slopes with minimal snow cover, caused erosion and downslope creep of soil material.[180] The main mechanism of creep was needle ice solifluction, whereby moisture freezing in the soil pushes soil grains up and out, followed by redeposition in a lower slope position. This downslope movement reached a maximum of five to seven centimeters per year in artificial fill areas that were poorly vegetated and subject to the additional disruption of cattle grazing in summer.[181] At ski areas in northern Japan, downslope soil movement also has been a problem, because grasses sown after trail construction fail to establish, leaving unvegetated patches.[182] Soil movement in Japan is attributed to erosion during snowmelt. Titus and Tsuyuzaki contrasted the Japan condition with a ski area in Washington State, where trail construction involved less mechanical slope contouring. Grassy vegetation has established itself well on the Washington ski slopes, and erosion has been minimal.[183] During spring snowmelt, Chase made qualitative observations of sediment-laden streamwater running off a ski area in Maine, compared to clear water in a nearby stream.[184]

As mountain resorts move toward greater four-season use, fertilizer applied to lawns around condominiums and resort facilities may lead to increased concentrations of nitrate and phosphate in streams.[185] Naturally occurring nitrate is also released from soils following soil disturbances, such as logging.[186] Fertilizer containing nitrogen and phosphorus may also be applied to ski trails to maintain the herbaceous cover.[187] Nitrogen and phosphorus are limiting nutrients in aquatic ecosystems. Increased nitrogen and phosphorus supplied to streams and ponds promotes unsightly algal

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[179] Johannes B. Ries, *Landscape Damage by Skiing at the Schauinsland in the Black Forest, Germany*, 16(1) MOUNTAIN RES. & DEV. 27, 27 (1996).

[180] *Id.* at 30.

[181] *Id.*

[182] Shiro Tsuyuzaki, *Species Composition and Soil Erosion on a Ski Area in Hokkaido, Northern Japan*, 14 ENVTL. MGMT. 203, 204–06 (1990).

[183] John H. Titus & Shiro Tsuyuzaki, *Ski Slope Vegetation at Snoqualmie Pass, Washington State, USA and a Comparison with Ski Slope Vegetation in Temperate Coniferous Forest Zones*, 13 (2) ECOLOGICAL RES. 97 (1998).

[184] Chase, *supra* note 115, at 60, 77.

[185] DUNNE & LEOPOLD, *supra* note 3, at 757–58.

[186] Martin & Pierce, *supra* note 162, at 278; Martin et al., *supra* note 162, at 209.

[187] Hornbeck & Stuart, *supra* note 99, at 36.

growth.[188] As excessive amounts of algae accumulate on stream or lake bottoms, the breakdown of this material by microrganisms consumes oxygen and may lead to dissolved oxygen levels unacceptably low for desired macroinvertebrates and fish.[189] Lawns and golf courses in particular may be sources of pesticide runoff to streams.[190] Recently, the town of Stowe, Vermont conditioned approval for a new golf course at the Stowe Mountain Resort on a very low pesticide application rate.[191]

As mentioned earlier, the two most important water quality factors that affect fish habitat, aside from sediment load, are dissolved oxygen and water temperature. These two factors are related, in that colder water can hold more oxygen.[192] Some fish species, including brook trout, brown trout, and slimy sculpin, thrive in cold, well-oxygenated waters.[193] Forest clearing for ski trails and other development allows sunlight to penetrate to the ground surface. Sunlight directly on a stream channel can have a dramatic heating effect.[194] When forested buffer strips are left along the stream channels, the temperature increase associated with forest clearing will be on the order of one degree centigrade, as opposed to up to five degrees centigrade in an unbuffered clear cut.[195] The cascades and ripples of a mountain stream tend to keep it well-aerated, which incorporates oxygen. A warming alone would threaten the trout population, but only a large input of nutrients could cause an algal bloom, which would consume all of the oxygen and eliminate other fauna.[196] This could happen in a snowmaking reservoir, but it is unlikely in a mountain stream.[197]

De-icing salts applied to parking lots and resort roads readily run off to streams, and they also mobilize heavy metals,[198] as documented at a ski area in New Mexico.[199] Road and parking lot sanding provides a ready source of sediment to runoff waters.[200] Ski resorts often must treat their own sewage,

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[188] DUNNE & LEOPOLD, *supra* note 3, at 755–60.

[189] *Id.* at 756.

[190] Scheuler, *supra* note 170, at 73–75.

[191] J. Dillon, *Stowe Deal Signed*, MONTPELIER TIMES ARGUS, June 13, 2001, at 1.

[192] DUNNE & LEOPOLD, *supra* note 3, at 719.

[193] CUSHING & ALLAN, *supra* note 138, at 68–69.

[194] Hornbeck & Stuart, *supra* note 99, at 36.

[195] *Id.*

[196] *See* DUNNE & LEOPOLD, *supra* note 3, at 756.

[197] *See id.* at 746 (discussing the importance of "turbulent mixing" in reaereation of oxygen depleted water).

[198] *Id.* at 735–36 ("[T]he effects of several metals can be synergistic, and their effects can be aggravated by other ions in solution.").

[199] James R. Gosz, *Effects of Ski Area Development and Use on Stream Water Quality of the Santa Fe Basin, New Mexico*, 23 FOREST SCI. 167, 176–77 (1977); Douglas I. Moore et. al, *Impact of a Ski Basin on a Mountain Watershed*, 10 WATER, AIR, & SOIL POLLUTION 81, 92 (1978).

[200] *Id.*

either with a plant or a large septic system. Mountainside or mountaintop facilities often have their own systems. Septic systems and treatment plant effluents pose the threat of leaking nutrients, *E. coli*, and other bacteria into adjacent streams.[201] White and Gosz, however, found no difference in bacteria counts in a stream above and below a ski area in New Mexico.[202] Some ski areas apply treated effluent to forested slopes to allow assimilation of the waste by natural processes.[203] Proposals at some ski resorts to use sewage effluent as snowmaking water have not gained enough public acceptance to implement.

Another commonly cited environmental issue at ski areas is the so-called "iron seep," caused where groundwater containing dissolved iron seeps from the ground. When the iron is exposed to oxygen it deposits as a red stain. Although not in itself harmful, the iron staining is an aesthetic issue, and is often treated with crushed limestone. Iron seeps commonly occur where fill that contains iron is added and terrain is altered to induce a rise in groundwater levels, such as in the construction of a snowmaking pond. Depleted oxygen in the groundwater zone promotes the mobilization of iron.

Mountain resort streams and undeveloped streams alike share the water quality effects of regional air pollution. Eastern North America receives inputs of acidic compounds and mercury as a result of long-range transport from industrial areas further south and west.[204] Forested mountain environments are particularly susceptible to these pollutants, because mountains receive higher rainfall, and the forest canopy is effective at filtering pollutants from the atmosphere. The snowpack and falling snowflakes also are effective at scavenging pollutants from the air. An acid rain study in the Laurel Highlands found that a Pennsylvania ski area had no effect on stream acidity.[205] Similarly, atmospheric mercury becomes incorporated in forest floor material, and when soil erosion occurs high concentrations of mercury may be released to streamflow, especially during high-flow episodes.[206]

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[201] Gosz, *supra* note 199, at 170 (discussing nutrients leaking from area septic systems).

[202] Carleton S. White et al., *Impact of Ski Basin on a Mountain Watershed*, 10 WATER, AIR & SOIL POLLUTION 71, 78 (1978).

[203] William Forney et al., U.S. Geological Survey, Land Use Change and Effects on Water Quality and Ecosystem Health in the Lake Tahoe Basin, Nevada and California, at 7 (2001) (discussing the effects of "spray disposal of secondary-treated sewage effluent" on Heavenly Valley Creek) *available at* http://pubs.usgs.gov/of/of01-418/of01-418.pdf.

[204] BLACK, *supra* note 2, at 320–21.

[205] William E. Sharpe et al., *Causes of Acidification of Four Streams on Laurel Hill in Southwestern Pennsylvania*, 13(4) J. ENVTL. QUALITY 619, 624–25 (1984).

[206] Timothy Scherbatskoy et al., *Factors Controlling Mercury Transport in an Upland Forested Catchment*, 105 WATER, AIR & SOIL POLLUTION 427, 435–37 (1998).

VI. CASE STUDY: MT. MANSFIELD

In September 2000, the U.S. Geological Survey, in collaboration with the Vermont Monitoring Cooperative and the University of Vermont, began a study to investigate the possible effect of a ski area on the timing and amount of runoff and sediment yield.[207] The study was modeled after the paired watershed approach, discussed earlier as the approach used in forest clearing studies. Researchers set up stream gages and sampling stations at two watersheds [Figure 3]. The West Branch watershed (11.84 square kilometers) contains the entire Stowe Mountain Resort. The Ranch Brook watershed (9.84 square kilometers) is adjacent and is nearly undeveloped. The two watersheds have similar climate, vegetation, topography, aspect, soils, and geology, but differ in land use. A state highway bisects the West Branch watershed (closed above ski area parking lot in winter), with a ski resort on both sides of the road. About twenty percent of the trees have been removed for ski trails, two base lodge facilities, and some vacation homes. The Ranch Brook watershed is completely forested, except for a network of cross-country ski trails and a short section of the auto toll road to the Mt. Mansfield summit. As the ski area was already present, predevelopment conditions could not be established. However, the current data collection will serve as a baseline if the resort carries out its proposed expansion in the West Branch basin.

Since the gages went on-line, streamflow has been recorded every five minutes. Suspended sediment monitoring began in the snowmelt period in April 2001, particularly during high flow periods. Analysis of sediment data at this early stage of the project has been limited.

Streamflow per unit area is consistently greater in the West Branch basin. The causes of this difference are under investigation, and likely result from differences in precipitation patterns, snow redistribution, and other factors. Aside from the absolute difference in magnitude of streamflow, the streamflow characteristics of the two watersheds are remarkably similar. In most storms, the shapes of the hydrographs (graph of streamflow versus time) are similar, and the timing of initial rise and peak flow are relatively synchronous [Figure 4]. The peak flow magnitudes tend to be larger at the West Branch watershed, in keeping with its consistently larger flow per unit area.

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[207] James Shanley is principal investigator of this project for the USGS on the initial Vermont Monitoring Cooperative grant, and has been interpreting hydrology and water quality. Beverley Wemple is principal investigator on subsequent grants from the Vermont Water Resources and Lake Studies Center for suspended sediment research and hydrologic modeling, and from EPSCoR (the U.S. government's Experimental Program to Stimulate Competitive Research) for evaluating the impacts of high elevation development on watershed processes.

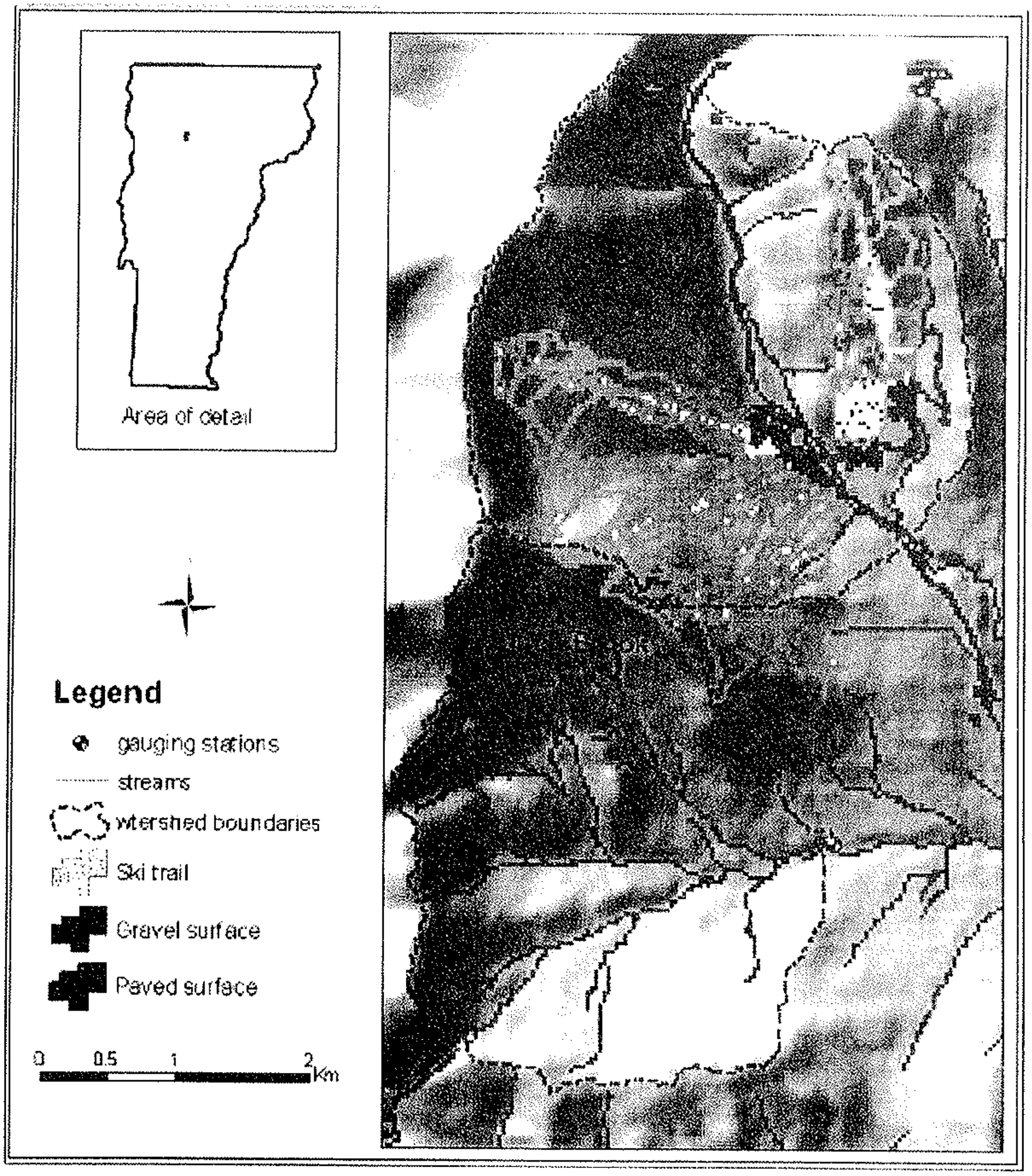

Figure 3. **Orthophoto showing outline of study watersheds on the east slope of Mt. Mansfield, Vermont. West Branch contains the entire Stowe Mountain Resort, while Ranch Brook is relatively pristine.**

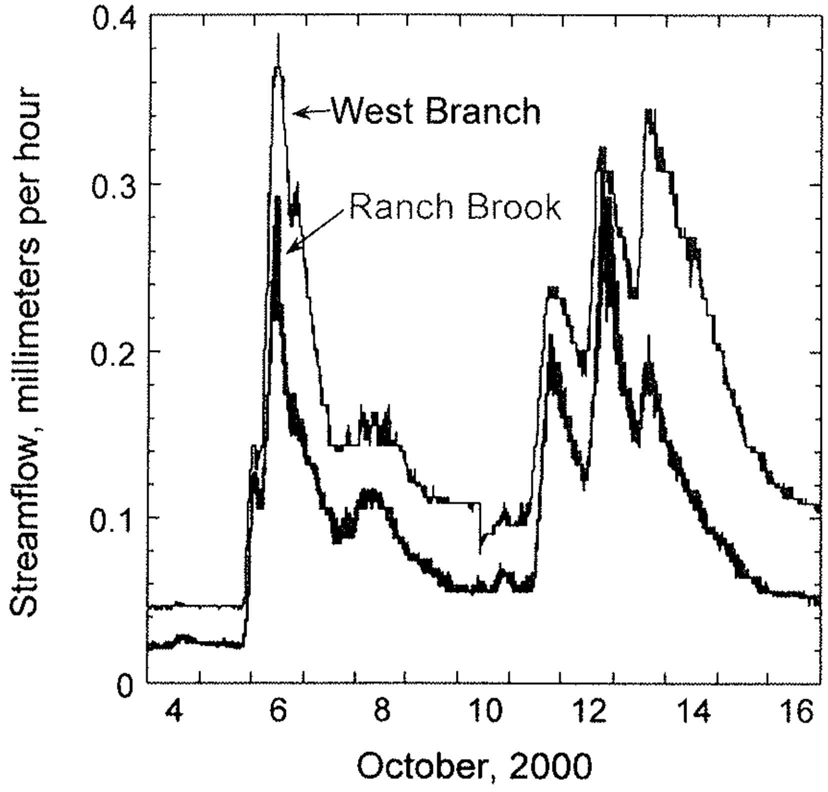

Figure 4. **Comparison of West Branch and Ranch Brook streamflow hydrographs during a series of rainstorms in the fall of 2000.**

There was somewhat more variability in the response to summer storms [Figure 5]. Although some of this difference may result from different rainfall patterns in the two basins, there was a consistent tendency for a sharper and more rapid response at the developed West Branch basin. Summer rainstorms tend to be high-intensity events that produce relatively small amounts of streamflow because most of the rain is absorbed by dry summer soils; this was especially true during the drought-like summer of 2001. The larger and more rapid response to small storms at West Branch, most notably on July 10, 11, and 17 [Figure 5], may be a result of rapid runoff over near-stream impervious surfaces associated with development in that basin. During the 2001 snowmelt period, unit area flows were higher for West Branch than for Ranch Brook during the initial melt but became nearly equal for the 2 sites as snowmelt progressed toward peak flow

[Figure 6]. Late in the snowmelt period, after the peak, flow at West Branch again became greater than that at Ranch Brook.

It should be noted that snow conditions in the winter of 2001 worked to minimize potential effects of development on differences in flow in the two basins. An unusual abundance of natural snow led to far less machine-made snow produced than in a typical year. Percentage-wise, machine-made snow made up very little of the snowpack and melting of the natural snowpack dominated both watersheds. Yet, the high diurnal peaks on May 1-4 and the sustained flow differential throughout May clearly showed that the snowpack persisted at West Branch and contributed meltwater to streamflow for a much longer time than at Ranch Brook. These results are consistent with the findings of Chase, discussed earlier, of synchronous hydrograph peaks (both watersheds peaked on April 24), and of Fallon and Bartsen of sustained melt runoff later into the spring.[208]

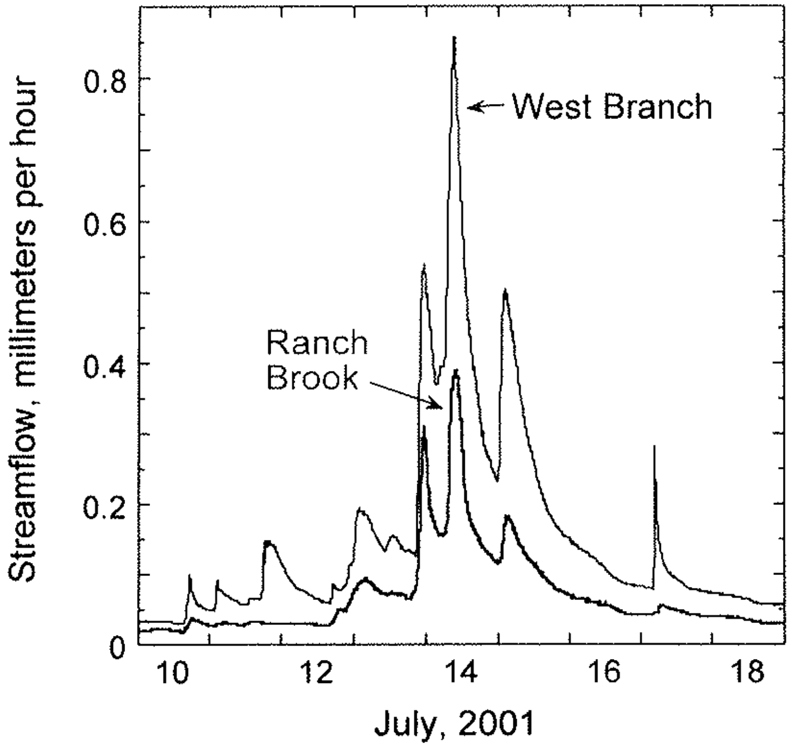

***Figure 5.* Comparison of West Branch and Ranch Brook streamflow hydrographs during a series of rainstorms in July, 2001.**

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[208] *See* Chase, *supra* note 115, at 60; Fallon & Bartsen, *supra* note 111, at 10.

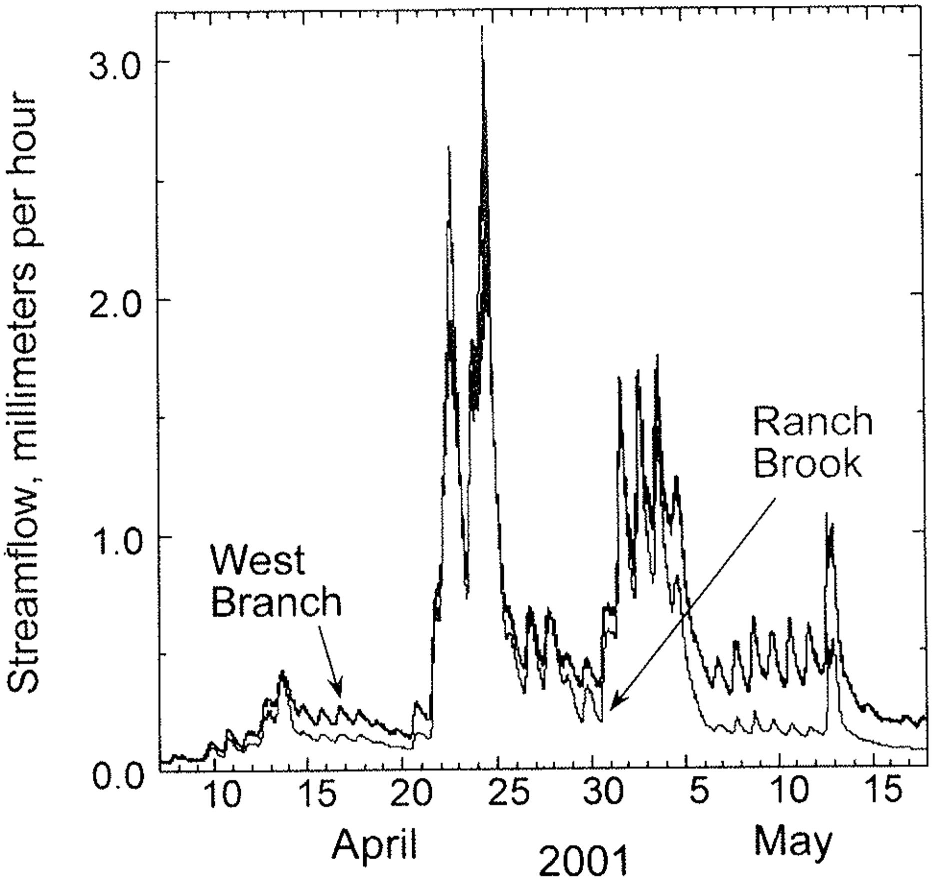

Figure 6. **Comparison of West Branch and Ranch Brook streamflow hydrographs during snowmelt 2001.**

Ranch Brook and West Branch watersheds each showed the expected positive correlation between total suspended solid (TSS) concentration and discharge, though there was considerable scatter in the data. TSS concentration is remarkably low at both basins, with maximum values of less than two hundred milligrams per liter during the 2001 winter snowmelt period [Figure 7]. The flushing of suspended solids occurred earlier and at lower flows in the West Branch basin than at Ranch Brook, while the highest yield of suspended solids in Ranch Brook occurred later in the snowmelt period. One possible explanation for these differences in sediment yield is that parking lots in the West Branch basin provide a source of fine sediment early in the snowmelt period.

VII. SCIENCE AS A BASIS FOR MANAGEMENT PRACTICE AND PUBLIC POLICY

This Paper has reviewed scientific studies on the effects of forest clearing on streamflow, the effects of forest roads on hydrology and sediment production, and the effects of impervious surfaces in a watershed to the biological health of its stream. Few of the studies discussed were conducted at ski resorts, thus there is some question as to their applicability to the mountain resort setting. Studies based on logging operations or urbanization cannot fully represent the situation at a ski area, but study

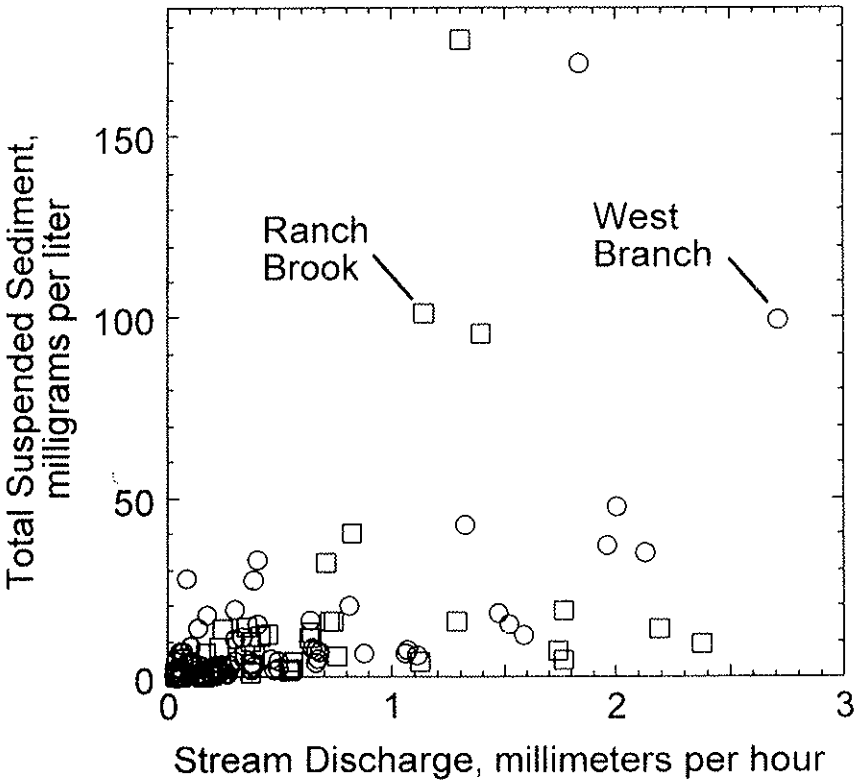

***Figure** 7.* **Relation between suspended sediment concentration and stream discharge at West Branch and Ranch Brook gages**

results provide guidelines that can be used by regulatory officials and land- and water-resource managers. In the absence of more specific data, extrapolating the results of these studies to ski areas is a reasonable next step. For example, study after study shows that forest clearing increases water yield and causes an initial flush of sediment and nutrients to streams.[209] With this awareness as a starting point, a resort can take measures to minimize and possibly eliminate these adverse effects.

We conclude with two brief examples of scientific considerations that have been useful to regulators. These examples involve Total Maximum Daily Load (TMDL) limits set by states in cases affecting ski resorts. A TMDL is set for a given pollutant based on scientific understanding of the maximum amount of the pollutant that an ecosystem can withstand. A ski resort in Vermont has had recurring violations of state water quality standards due to excessive sediment and nutrient runoff, and high stream flow caused by removal of streamside vegetation. As a condition of its permit to expand, the resort must implement a TMDL for sediment. This marks the first time a TMDL has been set for a ski resort.[210] A second TMDL case indirectly involves the ski industry: A TMDL has been set for phosphorous in a reservoir near Frisco, Colorado. As a result, ski resorts wishing to expand are held to their existing levels of phosphorous runoff.[211] The National Ski Area Association is advocating a voluntary approach to meet this type of water quality standard.[212]

CONCLUSION

High-elevation mountain environments are among the world's least resilient ecosystems. The very qualities that draw people to mountain ecosystems render them susceptible to adverse effects from development. These characteristics include: the steep slopes that attract skiers and hikers, but promote erosion; the cool temperatures that bring abundant snows, but which create a harsh environment for vegetation; the thin soils that give way to spectacular rock outcrops, but provide little buffer to store water or pollutants; and the beautiful mountain streams, whose balance of pools and riffles is easily upset by inputs of too much water or too much sediment or both. In some areas, such as the Rocky Mountains of the western United States, alpine areas are the prime source of water for downstream use by wildlife and humans, and maintaining its quantity and quality is imperative.

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[209] *See, e.g.*, Hewlett & Helvey, *supra* note 91; Hornbeck et al., *supra* note 87.

[210] Pelley, *supra* note 125, at 60A–61A.

[211] Pelley, *supra* note 125, at 61A.

[212] *Id.*

Despite the importance of mountain streams and their vulnerability to mountain development, the effect of mountain development on hydrology is under-studied and poorly understood. In compiling this Paper, the authors have made numerous inferences from research on the effects of forest harvesting and the effects of urbanization on streamflow, sediment export, and water quality. Research on mountain development *per se*, with a few notable exceptions, simply does not exist. Therefore, this overview is primarily a qualitative discussion of factors that, from a theoretical standpoint, ski area managers, or the recreational user concerned about his or her impact on the natural resource, should consider. As the pressure on mountain resources continues to grow rapidly, the need for more rigorous scientific study grows along with it. Lawmakers, policy makers, and land managers all need a greater scientific foundation on which to base their decisions on development in the mountain environment.