Appendix 2 - Narrative of Watershed Hydrology

Online Appendix to *The Boatman: Henry David Thoreau's River Years* (Harvard, 2014)

This appendix contains text that was originally written as segments designed to break up the historical and biographic narrative, but which were ultimately condensed into a single paragraph on page 188. The idea is that Thoreau's hydrology had a narrative, which begins with condensation and ends with river outflow over the Fordway. This narrative is what scientists call a "cascade," i.e. a continuous flow from one place to another.

The advantage here is that the text is much enlarged, and replete with Thoreau quotes. The disadvantage is that it is not edited to the standard of the finished book (one paragraph). The dates are citations to Thoreau's journal entries by data

Entry Cascade

The *annual* cycle of river rebirth begins with later winter breakup. But the *physical* cycle of rebirth begins when water falls from the sky in vapor, liquid, or solid form. Without this infusion from above, streams would quickly dry up and leave behind the stony skeletons of channel bottoms. This gravitational cascade of water can be as simple as rain falling on a rock in a brook, entering the flow, and streaming to the sea. But nearly everywhere else in the watershed, the story is far more interesting.

Condensation is the transition from vapor to liquid. Typically this begins within the atmosphere creating clouds of droplets so tiny they can't fall. Eventually, they enlarge, coalesce, and become heavy enough to precipitate as rain. The formation of frost and dew skips the step of precipitation. In this case, water it transferred directly from sky to land, usually when warmer, moister air overlies colder, drier terrain. When warm enough, we have dew: liquid films coat the surfaces of objects, especially those that are poor conductors of heat, like plant leaves. The films thicken, bead together, and enlarge into perfect spheres: "Each dewdrop takes the form of the planet itself… The surface of the globe is thus tremblingly alive." [May 13, 60] If thick enough, they flow or drip to the ground. On freshly plowed soil, droplets soak in before they flow. Henry witnessed this process one morning in May when there was "quite a fog till 8 A.M., and plowed ground blackened with moisture absorbed." Such dews contribute to river flow by adding a source of soil moisture that would otherwise be taken from the rain or snow. [May 17, 1860] If the ground is below freezing, the result is frost instead of dew. Technically, this isn't condensation, but deposition. Minerals of water --yes, ice is a perfectly respectable mineral-- spontaneously appear. Minute enough to scatter white light.

Snowfall is solid precipitation. Tiny six-sided "star crystals" are easily suspended by turbulent gusts. [Jan 5, 56] Eventually they reach a size where gravity pulls them down, perhaps gently as isolated, flake-like crystals, fast as a sodden masses of partly-melted crystals, or very fast as pellets of sleet. Snow is often a wintry mix of case histories.

Hail has quite a different story. Now the cold responsible for condensation is about altitude. When turbulent enough, updrafts within summer clouds can lift condensed water droplets so high that they freeze into pellets that enlarge concentrically as they remain in suspension. When the updrafts stop, however, hail falls from the sky like millions of icy marbles falling at terminal velocities. Sleet forms by a comparable concentric freezing process, but only on the way down through cold winter air.

Every speck of ice, whether frost, snow, hail, or sleet, will eventually thaw to liquid water, drain downward, and contribute to river flow, provided it escapes the gauntlet of evaporation. On January 2, 1854, Henry explored the pattern of a heavy snowfall. "The average of sixty-five measurements, up hill and down, was nineteen inches; this after increasing those in the woods by one inch each (little enough) on account of the snow on the pines. So that, apparently, it has settled about as much as the two last snows amount to. I think there has been but little over two feet at any one time." [Jan 2, 54] His measurements introduce another complexity to the process: the interception of precipitation by standing vegetation.

Henry had a whole lexicon for rain in his *Journal*. Drizzling, mizzling, and louring were light rains. Sojourning through the lightest rains was like walking through a heavy cloud, wetting you from the front, rather than the top. In contrast, a dark, thunderous, lightning-streaked cloud gave rise to a "blinding deluge." [Sep 16, 58] The heaviest rains caused flood wreckage, with roofs torn off, "trees town to pieces, the garden flooded at once, the garden flooded at once, corn and potatoes, etc., beaten flat." [Sep 16, 58].

In duration, rainfall might be a quick shower, lasting "about five minutes... and then suddenly, as it were in an instant, the wind whirled round to the westward, and clear sky appeared there and the storm ended." [Sep 16, 58.] Or there might be a "a succession of thunder-storms merged into one long thunderstorm, lasting almost continuously...two nights and two days." [Aug 9, 56] Or an enormous air mass might be wrung out, a "fisherman's rain" coming straight down in big drops, and lasting all day. In location, rain might arrive from everywhere at once from a thick stratus cloud. Or it might thunder in one corner of the sky, a "dark blue mass (seen edge wise) with its lighter upper surface--& its copious curving rain beneath & behind--like an immense steamer holding its steady way to its port--with tremendous mutterings from time to time--a rush of cooler air-- & hurried flight of birds." [Aug 31, 59] Rain usually came from the east and south, and clear dry air from the north and west.

Henry delighted in the variability and unpredictability of the weather. "How admirable it is," he once wrote, "that we can never foresee the weather,-- that it is always novel! [Dec 29, 51] Of course, he did discern patterns. Drenching subtropical storms were typical of late summer and early fall, being the inland consequence coastal hurricanes. The heaviest snows usually came after the winter solstice, with February blizzards being the most likely. Drenching Nor'easters -- technically extra-tropical cyclones-- were typically late fall and early winter events. Thunderstorms were characteristically summertime events, peaking in frequency during the humid-hot dog days of August.

Before becoming runoff, the snow and rain of winter and early spring were often held within the snowpack. Under the right conditions, this could be quickly released, usually when a steady spring rain fell on a deep winter snow pack previously brought to the sodden, slushy stage, yet resting above frozen ground. The result was "unfathomable water beneath the snow." [Dec 28, 51]. The annual spring freshet of the Concord River would soon commence.

Runoff Cascade

Falling water has two choices. If the ground is frozen, the gate of the soil is closed, and runoff is the result, whether as sheet flow, rills, and puddles. If thawed, the gate is open, allowing the water to saturate the soil and seep downward to recharge aquifers that will later augment summer flow.

The gate is shut during the "the peculiar and interesting Brown Season of the spring," which "lasts from the time the snow generally begins to go off --…till the frost is generally (or entirely?) out." During this season "the surface of the earth is never so completely saturated with wet ..., for the frost a few inches beneath holds all the ice and snow that are melted in the rain, and an unusual amount of rain falls." [Apr 5, 59] "This season of rain and superabundant moisture makes attractive many an unsightly hollow and recess. I see some roadside lakes, where the grass and clover had already sprung, owing to previous rain or melted snow, now filled with perfectly transparent April rainwater, through which I see to their emerald bottoms." [April 24, 56]

At this season, the landscape is a mosaic of wet and wetter: "patches of bare ground and snow much running water." [Jan 13, 54] After months of quiet, the surge of flow is inspiriting: "A little brook crossing the road ... a few inches' depth of transparent water rippling over yellow sand and pebbles, the pure blood of nature. How miraculously crystal-like, how exquisite, fine, and subtle, and liquid this element, which an imperceptible inclination in the channel causes to flow thus surely and swiftly." [Jul 23, 51] "On the east side of Ponkawtasset... There is quite a waterfall beyond where the old dam was. Where the rapids commence, at the outlet of the pond, the water is singularly creased as it rushes to the fall, like braided hair, as the poet has it." [Apr 21, 52]

Stunning geometric patterns emerged from shallow, rapid surface flow, especially the herringbone pattern of sheet runoff:

> I see now... interesting ripples which I only notice to advantage in very shallow running water... The water, meeting with some slight obstacle, ever and anon

> appears to shoot across diagonally to the opposite side, while ripples form the opposite side intersect the former, producing countless regularly and sparkling diamond-shaped ripples... a regularly braided surface, tress-like... The [158] ripples are as rectilinear as ice-crystals." [Feb 21, 60]

Counter-intuitively, heavy spring rains could dry up the soil because they help open the gate to downward seepage where "the earth is so dry it drinks like a sponge." [May 12, 60] He witnessed this on March 19, 1857. "Heavy rain in the night and to-day ... taking the frost out, the water that stood on the surface is soaked up, so that it is even drier and better walking before this heavy rain is over than it was yesterday before it began... [Mar 19, 57]

Also opening the gate in the downward direction is the positive feedback that takes the ice out. "Expect rain [59] after rain till the frost is completely out. The melted frost, rising in the form of vapor, returns perhaps, in rain to liberate its kind still imprisoned in the earth." [Mar 18, 59]

Timing is everything. A cold, snowless December and January will cause the ground to freeze about two feet deep. A snow after that helps insulate the frozen layer from late winter warmth, thereby keeping the gate closed, and the aquifers only slightly recharged. In contrast, a warm early winter followed by thick snow insulates the ground from freezing deeply, keeping the gate open for snowmelt recharge.

Different flood scenarios result as well. Copious spring runoff from rapid snowmelt and heavy rain on frozen soils leads to a powerful spring freshet and a more likely summer drought. Such wwould be a good season for haying, given a potent early dose of water and nutrient, followed by firm, dry meadows. Conversely, conditions of slow snowmelt and gentle spring rains on unfrozen soil sends copious water downward to aquifers, keeping summer stage high and making the hay harvest riskier.

Aquifer Cascade

Apart from surface evaporation, nearly every drop of water that isn't shunted sideways as overland flow, moves downward into the darkness into the groundwater realm. Initially, excess water coats mineral grains, which thicken until water can no longer be absorbed. At that point, the excess trickles downward as a wetting front. When everything is soaked all the way down to the water table, any additional seepage raises it locally, thereby increasing the volume of water stored. Aquifers can be recharged at any time of the year. But the biggest slug always comes during the spring, when snowmelt combines forces with drenching warm rains at a time when the plant leaves aren't using water .

Henry used the phrase: "bowels of the earth" to describe what we call aquifers. These masses, fed by infiltrated rain, were the sources of perennial springs he identified, named, examined, and sampled as part of his river project. Most of these, he discovered, emerged "distinctly just at the base of a hill or bank and on the edge of a meadow or river. Apparently the water which percolates through the hill or upland, having reached a stratum saturated with water and impervious to it, bursts out in a spring." [Jul 7(?), 60] "Each one is the source of a streamlet which finds it way into the river." [Jul 7, 60]

Springs were a source of great delight during his sojourns, especially in summer: "I drink at every cooler spring in my walk these afternoons and love to eye the bottom there…It would be worth the while, methinks, to make a map of the town with all the good springs on it, indicating whether they were cool, perennial, copious, pleasantly located, etc. " [Jul 12, 57] He followed through on this idea during the final phase of his 12-task river project. The springs we cannot see are those that enter bodies of water. Instead, we can feel them with our feet as a thin layer of cold water flowing in near the bottom.

Draining into the river for the full 22 miles of its length, and into every perennial brook in its watershed is the slow-but steady drainage of groundwater from flanking aquifers. This is water that went down to the "bowels" when the gate of frozen ground was open, rather than than sideways when it was shut. By late summer, especially in drought years, aquifer drainage becomes the exclusive source of stream flow, responsible for everything below what Henry called "summer level." This wasn't a steady stage, but a threshold level marking the transition between freshet and spring flow.

Brook Cascade

Several hydrological steps earlier, brooks helped convey excess runoff shunted sideways by frozen ground. Now they were fulfilling their second task, becoming drains for whatever water went deep underground into aquifers. This second task explains why the head of flow migrates progressively downstream as the water table descends.

Henry described the transition this way: "Many a brook will have run itself out and now be found reduced within reasonable bounds." [Jan 23, 55] The phrase "run itself out" refers to the quick surface runoff, which can be "accomplished" in a single night. The phrase "reasonable bounds" reflects the later discharges from shallow subsurface storm flow, combined with the more long-lasting base flow coming from aquifers.

Though nearly every brook follows this same basic pattern, each has its own variation. Some, like Dodges Brook, appear and disappear mysteriously. Henry noted that it was "dry and then again, after a week of dry weather in which no rain fell, it would be full again. [May 31, 53] Cold Brook also had an interesting pattern: "Rice says that the brook which crosses the road just beyond his brother Israel's is called Cold Brook. It comes partly from the Dunge Hole. When the river is rising it will flow up the brook a great way. [Nov 19, 55] On another occasion, he describes the same brook differently: "Mr. Rice says that the brook just beyond his brother Israel's in Sudbury rises and runs out before the river, and then you will see the river running up the brook as fast as the brook ran down before." Even "Mill Brook," on which Concord was founded, was flashy, despite running on a very low gradient across the Bedford Flats. Thoreau noted that it "rises faster and higher comparatively than the river." [Apr 3, 56]

A shifting groundwater divide, or a bulge of groundwater recharge could explain such behavior. During full summer, rapid daytime evapotranspiration subtracts water that would have otherwise drained away, toggling brooks into and out of existence on a diurnal schedule. This likely explains the rill between Hosmer and Simon Brown that "generally runs all night and in the fore part of the day, but then dries up, or stops and runs again at night, or it will run all day in cloudy weather." [Oct 19, 58].

Sometimes there's no explanation for a brook's behavior: Thoreau once noted "two ravines in other respects exactly similar," but "in the one there is a stream which drains it, while the other is dry!" [Nov 8, 57] In another, "this stream is here sometimes quite lost amid the rocks, which appear as if they had been arched over it, but which, in fact, it has undermined and found its way beneath, and they have merely fallen together archwise, as they were undermined." [Nov 4, 51]

This was the case for Saw Mill Brook, "a brawling mountain stream" with "rocks out of all proportion to its tiny stream," looking "as if a torrent had anciently swept through here." [Nov 4, 51] Some brooks are little more a series of small waterfalls. "We love to see the water stand, or seem to stand, at many different levels within a short distance, ... many successive falls in different directions, meandering in the course of the fall, rather than one "chute," --rather spreading and shoaling than contracting and deepening at the fall." [Apr 1, 52] Clearly, groundwater drainage is now taking place through a series of clear pools and miniature waterfalls created by much more powerful surface flows, whether of glacial age or not.

At this point in the hydrological cascade, the physics changes. No longer is the main story about melting, soaking, trickling, rilling, or being squeezed through sand grains by pressure. Now the story is about open-channel-flow, the joyful friction between the bed and banks manifesting itself as turbulence. Without this friction, flow would accelerate to the sea. What happens instead is that each channel becomes its own self-contained physical system. For every combination of discharge, bed shape, bed roughness, and channel gradient, there is a "Goldilocks" velocity of just right. Faster flow increases turbulence, which slows things down. Slower flow decreases turbulence, which speeds things up. Steady state equilibrium appears.

Reservoir Cascade

Some swamps, and ponds have no inlets. They are the sources of brooks, rather than wide spots along the way. "Spring like" is the phrase Henry used for the "clear crystalline water flowing out of a swamp over white sand and decayed wood." [Jul 17, 52] It's actually spring water, merely held for a while basins until it flows over whatever threshold is there. [Jul 6, 53]

In contrast, swamps, ponds, and reservoirs with inlets, however, are buffers for the streams draining through them. By temporarily storing water, they change the timing of inflows and outflows. Strong pulses coming in are dampened such that the outlets convey gentler, longer pulses of discharge going out. Fair Haven Pond provides a perfect example. It dampens flows coming at it from either directions, faster in than out.

In 19th century Concord, artificial reservoirs were far more important in buffering streams than natural ponds. Every time the gate of a dam was closed, the output goes to zero and the storage rises at a rate set by the inlet stream. When the gate's opened, that temporary storage is released to produce stronger outlet flows for shorter periods of time. Thoreau provided an example: "Sam Barrett tells me on the 19th that he has so little water [coming in] that he has raised his gate only 3 or 4 times for a fortnight." [Aug 14, 59, Prince] When the reservoirs are full, however, the water simply flows over the dam with no change in storage.

With upwards of 80 factory reservoirs on the headwaters of the Assabet and Sudbury Rivers above the meadowlands, the sum total of all these effects on the river was substantial. During his river project, Henry was the only one to measure it accurately. [Sep 16, 51]

Flood Cascade

Rills merge into brooks, which merge into larger brooks, which merge into the Assabet and Sudbury Rivers, which merge to create the Concord River at Egg Rock. Mass has increased steadily. Something quite different happens at the Fordway, the natural outlet of the bedrock basin in Billerica. Like a the open drain of a lavatory sink when the faucet is wide open, it's not efficient enough to pass the mass arriving, so the water level rises. Here's why.

Beneath the Fordway is a nearly flat reach of solid granite bedrock that is resistant to being widened or cut down. It's topographically rough as well, full of boulders and small ridges of rock. This roughness forces the water to flow above and around obstacles. This is analogous to the crowd of people backing up at turnstiles, with a few jumping over. Were the channel wider, the slope steeper, and the bed smoother and deeper, the water pouring down from the catchment would easily drain away. Instead, these factors combine to back up the water. Still the system is inefficient because the increase in velocity caused by deeper water raises the turbulence, which keeps the velocity in check. Were Musketaquid a normal river, a rise of a few feet might back up the water a mile or two up the channel. But in this case, the $2^{1/2}$ feet of rise that Thoreau documented here is sufficient to put the entire 25 mile-long lake basin underwater with wide and narrow spots.

And because great volume of water can be stored in this large alluvial basin, these transient floodplain lakes can last for many weeks, long enough to be cleared of all suspended sediment. The happy result is that the meadows are fertilized and the adjacent aquifers are recharged to ensure that the channel never runs dry.

Exit Cascade

Every drop of water that isn't evaporated from the surface eventually flows over the outlet at the Fordway. The simplest path is a simple rain drop falling on the stream and flowing over the lip of the Fordway and out of the bedrock basin. Alternatively, it may have taken any one of an infinity of complex paths: into and out of the forest canopy, snowpack, frozen ground, aquifers, into the stream, being backed up into lakes, recharging the marginal aquifers, draining back out of them, and so forth. But no matter what, every liquid drop eventually leaves the alluvial valley through the Fordway Once over this outlet, the flow becomes concentrated into The Falls, about which I've said little, because its hardly a fall anymore, having been partially drowned by the Billerica Dam. Today, it's mainly a zone of rapid flow. No longer is this farm-water. Rather, it's industrial water, flowing past four dams before reaching the Merrimack, where it joins the throng of molecules flowing to the sea. Upon touching the Merrimack, Concord River no longer exists.