SCIENTIFIC BRIEFING

HP TODAY

HYDROLOGICAL PROCESSES
Hydrol. Process. **18**, 3447–3460 (2004)
Published online in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/hyp.5740

Robert E. Horton's perceptual model of infiltration processes

Keith Beven*

Environmental Science, Lancaster University, Lancaster, UK

*Correspondence to:
Keith Beven, Environmental Science, Lancaster University, Lancaster LA1 4YQ, UK.
E-mail: k.beven@lancaster.ac.uk

Abstract

Robert E. Horton is best known as the originator of the infiltration excess overland flow concept for storm hydrograph analysis and prediction, which, in conjunction with the unit hydrograph concept, provided the foundation for engineering hydrology for several decades. Although these concepts, at least in their simplest form, have been largely superseded, a study of Horton's archived scientific papers reveals that his perceptual model of infiltration processes and appreciation of scale problems in modelling were far more sophisticated and complete than normally presented in hydrological texts. His understanding of surface controls on infiltration remain relevant today.

Key Words history of hydrology; macropores; sun-checks; soil air; infiltration capacity; scale

The Horton Papers

Robert Elmer Horton (1875–1945) is celebrated in the hydrological literature as the originator of the idea that storm runoff is primarily a result of overland flow generated by an excess of rainfall over the infiltration capacity of the soil. He expressed the concept thus (Horton, 1933: 446–447):

> Infiltration divides rainfall into two parts, which thereafter pursue different courses through the hydrologic cycle. One part goes via overland flow and stream channels to the sea as surface runoff; the other goes initially into the soil and thence through ground-water again to the stream or else is returned to the air by evaporative processes. The soil therefore acts as a separating surface and ... various hydrologic problems are simplified by starting at this surface and pursuing the subsequent course of each part of the rainfall as so divided, separately.

Elsewhere Horton suggested that the soil surface acts as a 'diverting dam and head-gate' (Horton, 1933: 446) or 'sieve' (e.g. Horton, 1936a: 404; 1937a: 1018). The process of surface runoff generation by this mechanism is now known as Hortonian overland flow or infiltration excess overland flow (though Horton himself does not appear to have used this phrase, preferring *rainfall-excess*; Horton, 1933, 1935).

One of the reasons why the rainfall-excess concept continued to permeate hydrological analyses and models for so long after Horton's death was that it provided a simple, yet apparently process-based, method of predicting the response of basin areas, especially when combined with the *unit-graph* theory of LeRoy K. Sherman (1932) as a way of distributing the resulting rainfall-excess in time to form a hydrograph. Undoubtedly, this had much to do, initially at least, with the fact that Horton was also a practising and pragmatic hydraulic engineer who applied his conceptual ideas to a wide range of applications in the USA and elsewhere. An application to the data set collected at his Horton Hydrological Laboratory at Voorheesville, New York, is described in detail in Beven (2004a). However, Horton was also a very good and careful scientist who made contributions to hydrological science spanning the whole range of the terrestrial and atmospheric parts of the hydrological cycle (e.g. see Hall (1987), Dooge (1992) and Brutsaert (1993), and the culmination of his scientific work on terrestrial hydrology and geomorphology, Horton (1945a), published in the year of his death). His understanding of infiltration and runoff production mechanisms, as revealed in his scientific papers, turns out to be much more sophisticated than is normally represented in hydrological texts.

The 94 boxes of Horton's papers are now in the National Archives II at College Park, Maryland. The list of boxes reads like the table of contents of a complete hydrological text book (see Table I).[1] Boxes 59, 61 and 62 contain materials for a manuscript for an extended monograph on the *Infiltration of Rainfall* with numerous inserts, hand-written alterations and sketched diagrams. This appears never to have been finished or published. Other boxes contain background material, results from infiltration experiments, analyses of infiltration experiments carried out by others and exchanges of letters with other American hydrologists concerning the results and the terminology of infiltration and related hydrological processes (see also Beven (2004a,b)).

In modern hydrological texts, the presentation of Horton's ideas is generally limited to his infiltration equation (see below) and the idea of the storm hydrograph being generated by infiltration excess overland flow. Hornberger *et al*. (1998: 207) mention Horton only in passing in reference to infiltration excess overland flow noting that Horton 'reported occurrences of this runoff mechanism'.

Looking further back, Horton did not contribute to the hydrology text edited by Meinzer (1942), though his collaborator Harry Leach did in the chapter on the hydraulics of overland flow. The chapter on infiltration by Sherman and Musgrave does not mention Horton's infiltration equation (or, in fact, any predictive equations).

In Linsley *et al*. (1949), however, Horton receives more citations than any other hydrologist. His work is cited on the measurement and areal interpolation of rainfall, rainfall depth–area curves, mapping evapotranspiration, weir coefficients and stream gauging, interception, the hydraulics of sheet flow and roughness coefficients, infiltration theory, flood waves, and flood frequency. They discuss 'the infiltration approach' to basin-scale rainfall-runoff estimation (p. 424ff), following the review of the method by Cook (1946) who had worked with Horton[2] (though they give clear preference to the coaxial graphical methods they had themselves pioneered for the US Weather Bureau).

The phrase 'Hortonian overland flow' seems to have been introduced by Kirkby and Chorley (1967). Linsley *et al*. (1982: 240) later refer to overland flow that is 'non-Hortonian' in referring to overland flow produced on saturated soils. In fact, Horton himself recognized the possibility of soils being maintained at saturation by subsurface flows, resulting in areas of the basin producing runoff at almost the same rate as the rainfall intensity (see Horton (1936b) and discussion in Beven (2004b)).

Horton's Perceptual Model of Infiltration Processes

In his seminal paper of 1933, Horton introduces his basic ideas about infiltration capacity as a control on surface runoff and the consequent possibility of subdividing the discharge hydrograph into two components, that of surface runoff derived from the 'rainfall-excess' and that of ground-water flow that is maintained by the water infiltrated into the soil in

[1] Further papers are held by Albion College, MI in the Stockwell-Mudd Libraries (see http://www.albion.edu/library/specialcollections/CollegeCollectionsList.asp).

[2] And married his daughter (USACE, 1997).

past rainfall events. He discusses at length the factors affecting infiltration capacity. For a natural soil, he envisaged a pattern of change in infiltration capacity for each storm period based on his own observations at the Horton Hydrological Laboratory.

> Starting with a maximum value when rain begins, the infiltration-capacity decreases rapidly at first as the result of the operation of some or all of the following processes: (1) packing of the soil-surface by rain; (2) swelling of the soil, thus closing sun-checks and other openings; (3) inwashing of fine materials to the soil-surface openings.[3]
>
> These effects are confined to a thin layer at the soil-surface. Infiltration-capacity during rain is, therefore, generally less than the gravitational transmission-capacity within the soil mass. This is the principal reason why soils free to drain are not seldom if ever fully saturated during rain, however intense or prolonged. Another reason is the necessity for escape of air as fast as the water enters the soil. This reduces the pore space available for water within the soil...
>
> After rain ends, restoration of the infiltration-capacity begins. Wind-action and differential temperatures close to the soil surface aid in reopening the soil-pores, shrinkage of colloids takes place, perforations of earthworms and insects are restored, and the infiltration-capacity returns to its maximum value usually within a period of a day or less for sandy soils, although several days may be required for clays and fine textured soils.
>
> (Horton, 1933: 450–451)

He repeats this emphasis on the role of surface effects on infiltration capacity elsewhere:

> The infiltration capacity of a soil may greatly exceed the transmission capacity as determined in the laboratory if the soil contains numerous earthworms, insect, root and other perforations which permit air and water to flow through the natural soil pores. Also the infiltration capacity may greatly exceed the interior body of soil if the soil surface has recently been loosened by cultivation or opened by drying and sun-checking. On the other hand the infiltration capacity may be much less than the transmission capacity of the interior body of soil if the soil surface has been poached by rain {or puddled by the trampling of livestock}.[4]
>
> [Box 59: typed manuscript on Relation of Infiltration Capacity to Field Moisture Capacity of Soils, initialled REH, dated 8 June 1933]

He also notes that in cultivated soils a more complex pattern of change may occur. This was expressed later in *Infiltration of Rainfall* in a section titled *A Phase Rule of Infiltration* as follows:

> The cycle of changes in infiltration capacity for a loose, cultivated or sun-checked soil containing colloid material, from the beginning of rain through to the beginning of the next subsequent rain, is as shown by [Figure 1]. The following phases occur:
>
> oa, Packing or packing and in-washing, rapid decrease.
>
> ab, Colloidal readjustment; much slower decrease than in packing phase; may also involve in-washing to surface pores.
>
> bc, Stable phase; constant infiltration capacity as long as rain lasts.
>
> cd, Drying or restorative phase, after rain ends. This may be at first slow, then more rapid due to sun-checking, the opening up of earthworm and {~~miscellaneous~~ insect and other}[5] perforations.
>
> de, The maximum phase for packed soil surface. The initial rate for uncultivated lands would be the same and the initial packing phase would disappear except for soil surfaces which crumble on drying.
>
> The vertical line ef indicates cultivation, the infiltration capacity immediately increases to

[3] Flow through sun-checks is described as a form of 'concealed surface runoff' in Horton (1942: 481), and it is clear from several pages of notes in Horton's hand [Box 71], in which he tries to work out a theoretical description for flow around hexagonal blocks, that in using this term he had in mind flow in a *downslope* direction *around* blocks of soil cracked to a certain depth rather than a form of subsurface stormflow.

[4] Text in braces is in Horton's hand on original typescript.

[5] Deletion and text in braces is in Horton's hand on original typescript.

Table I. List of boxes of Horton papers (National Archives R.G. 189). The boxes were catalogued and listed by A. Hecht, 19 July 1951. Current reference is RG189 A1/Entry 5 Horton Papers, Stack Area 130, Row 19, Comp25, Shelf 6+

Box 1	Hydrological Cycle	Box 20	Channel Dynamics and Sediment Transport, Vertical Velocity Curves	Box 39	Daily Rainfall Distribution
Box 2	Glossary of Hydrologic Terms	Box 21	Vertical Velocity Curves	Box 40	Rainfall Intensities
Box 3	Glossary of Hydrologic and Related Terms	Box 22	Non-Uniform Flow and Flood Waves	Box 41	Rainfall Intensity and Infiltration Studies. 24hr Rainfalls
Box 4	Hydrodynamic Universe, Atomic Structure, Plants	Box 23	Channel Charact. and Flood Waves	Box 42	Raindrop Size. Rainfall Depth–Area Relations. Thunderstorms.
Box 5	Hydrodynamic Universe, Earth as a Drainage Basin	Box 24	Flood Wave Experiments	Box 43	Rainfall Characteristics
Box 6	Geomorphology (Land Forms)	Box 25	Flood Wave Hydrographs, Lab. Exps.	Box 44	Climate and Climate Indices. Sun Spots
Box 7	Morphology of Drainage Basins	Box 26	Wave Research of Darcy and Bazin	Box 45	Temperature in Relation to Hydrology
Box 8	Morphology of Drainage Basins (etc.)	Box 27	Flood Wave Theory, Meteorological Limitations, Flood Predictions	Box 46	Temperature Data
Box 9	Geomorphology of Streams	Box 28	Flood Producing Capabilities, Flood Frequencies	Box 47	Evaporation in Relation to Altitude and Temperature
Box 10	Physiography	Box 29	Flood Papers with Translations	Box 48	Evaporation Theory and Data
Box 11	Regional Runoff	Box 30	Flood Analyses, Flood Frequencies	Box 49	Evaporation and Percolation, European Evap. Records
Box 12	Runoff in Relation to Rainfall. Swamps and Marshes	Box 31	Flood Frequencies, Flood Formulas	Box 50	Evaporation and Water Losses
Box 13	Land Drainage	Box 32	Statistical Methods and Theory	Box 51	Evaporation and Water Losses
Box 14	Physics of Water	Box 33	Snow, Ice, Glaciers, Winter Flow of Streams	Box 52	Water Loss Studies by Drainage Basins
Box 15	Hydraulics of Fluid Flow	Box 34	Snow and Ice	Box 53	Transpiration, Crop Water Requirements
Box 16	Hydraulic Formulas	Box 35	Rain Gages and Snow Measurement	Box 54	Water Losses
Box 17	Hydraulic Papers and Translations	Box 36	Meteorology, Phsychrometry	Box 55	Consumptive Use and Water Losses
Box 18	Pipe Friction	Box 37	Dynamic Causes of Precip. Rainfall Data, Concho Basin Studies, India Data	Box 56	Lysimeters. Evap. from Soils
Box 19	Weir Experiments, Bazin, USDA, USGS	Box 38	Rainfall in Relation to Topography and Elevation	Box 57	Soil Type, Classes, Constants

Box 58	Soils and Soil Moisture	Box 71	Base-Flow Separation	Box 83	Flood Control. Resvr. Storage Regulation
Box 59	Infiltration Experiments	Box 72	Duration Curve Data. Minimum Flows	Box 84	La Grange Book Data
Box 60	Infiltration Studies	Box 73	Ground Water in Relation to Runoff	Box 85	Streamflow and Met Data Collected at Horton Laboratory
Box 61	Infiltration	Box 74	Ground-Water Geology	Box 86	Hydrology of Meshaminy, Tohickon, Perkiomen Creeks, PA
Box 62	Infiltration and Interception	Box 75	Ground-Water Theory	Box 87	Muskingum Basin and Illinois Stream, Homer–Flynt Runoff Graphs
Box 63	Sprinkled Plot Exps.—Misc.	Box 76	Ground-Water, Well Yields	Box 88	Ralston Creek, Iowa, Studies
Box 64	Sprinkled Plot Exps.—Arizona	Box 77	Ground-Water Records, Hydraulics	Box 89	Power Potential in Delaware Basin. Delaware Flood Crest Velocities
Box 65	Mechanics of Surface Runoff	Box 78	Ground-Water, Specific Yield, Capillary Flow Experiments	Box 90	Hydrology of Delaware River Basin
Box 66	Surface Runoff Mechanics	Box 79	Diurnal Variations in Ground-Water	Box 91	Rainfall, Wind Velocity Near Ground
Box 67	Surface Runoff, Runoff Coefficients	Box 80	Hydrology of the Great Lakes	Box 92	Hydrology—General
Box 68	Surface Runoff Analyses	Box 81	Limnology, Lake Temp. & Evap.	Box 93	Delaware River Studies. Salinity and Pollution
Box 69	Unit Hydrographs and Channel Inflow	Box 82	Reservoir Capacity Analysis. Flood Regulation	Box 94	Delaware River Studies. Reservoir Survey Notes
Box 70	Channel Storage				

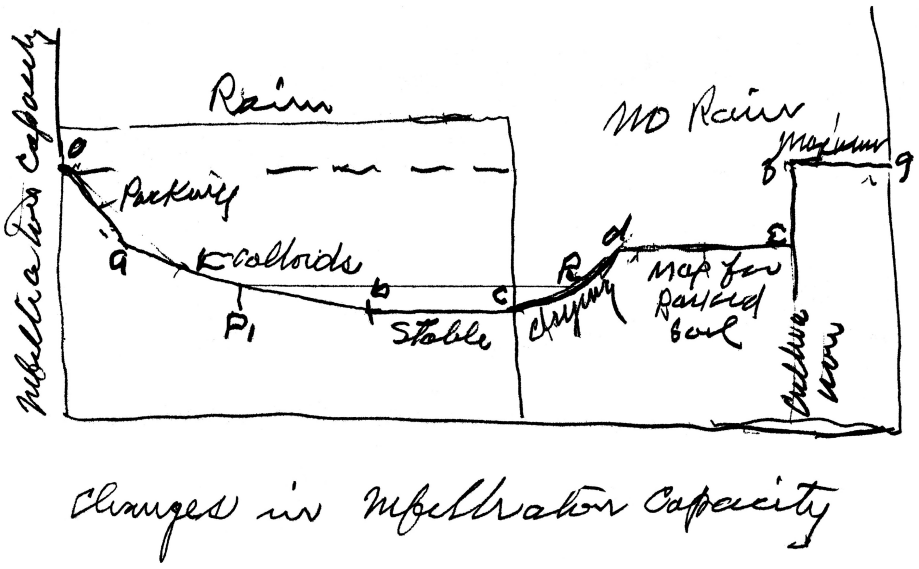

Figure 1. The phase rule of infiltration [Box 61: Manuscript Infiltration and Rainfall, original drawing in pencil p. 82]

the maximum phase fg, with the infiltration capacity equal to the assumed initial value o.

Of course, either the rain or the subsequent dry period may not last long enough for the completion of the cycle. If the rain period is interrupted, for example, before the stable phase is realized, restoration begins at once and the dry half of the cycle is completed from that point on, if the dry half of the cycle is interrupted by rain the restoration begins at the value of the infiltration capacity then pertaining.

[Box 61: Manuscript of *Infiltration of Rainfall*, pp. 82–83]

Horton notes that these effects can be expected to lead to seasonal changes in maximum infiltration capacity, as well as the short-term changes during storm periods. In a number of papers he comments on the seasonal change in infiltration capacities, including the effects of snow and frost (Horton, 1945b) and temperature effects on viscosity. However, Horton (1940: 416) notes:

> While temperature is quite certainly a factor, the author believes that biological factors are the principal cause of the seasonal cycle of infiltration-capacity. In case of cultivated soils there is a marked increase of infiltration-capacity immediately following cultivation. A marked rise of infiltration-capacity also occurs at about the time in the spring when earthworms, ants, beetles and other soil fauna become active, and a marked decrease of infiltration-capacity occurs in the fall at about the time they become dormant. That the two causes enumerated are principal factors in the seasonal variation is indicated by the wide range of infiltration-capacity at these times of year [Figure 2].

Horton and the Infiltration Capacity Concept

Critical to Horton's views on infiltration was the idea of infiltration capacity (Horton, 1933, 1940). Horton realized that, as the soil wets and dries, the rate at which water can infiltrate into the soil will change, but that at any time there will be a limit, the infiltration capacity, that will be the maximum rate at which rain falling on the soil surface can infiltrate. He also realized that rainfall falling at rates less than the infiltration capacity of the soil would all infiltrate and, therefore, that it was important to distinguish between the terms infiltration rate and infiltration capacity. It seems, however, that he had some difficulty convincing some other hydrologists of this, partly because 'to the minds of some, the word capacity connotes a

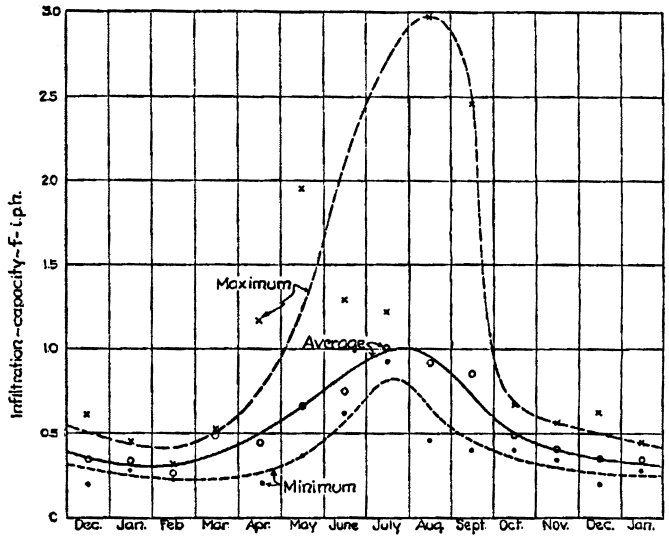

Figure 2. Seasonal changes in minimum and maximum infiltration capacities (from Horton (1940: 416))

volume, whereas infiltration-capacity denotes a rate' (Horton, 1942: 480). Horton expounded at some length on this issue in his 1942 paper on Hydrologic Terminology (dealing also with the use and misuse of the terms percolation, absorption, and intake). He seems to have been a stickler for the proper use of (his own) terminology and was, at times, roused to the point of sharpness:

> With reference to the expression 'infiltration capacity' I have found to my chagrin that there are particularly in the Soil Conservation Service men who allege that they do not have sufficient mental capacity to visualize the meaning of the word 'capacity' with but one of its well accepted uses in physics and hydraulics, viz. as a volume. The Oxford English Dictionary gives as the first definition of the word 'capacity': 'ability to take in; ability to receive or contain'.[...] For the benefit of those having the limitations of mental capacity above suggested, it may be well to point out that infiltration capacity is a volume per unit of time. A third definition of 'capacity' given in the Oxford dictionary is 'mental or intellectual receiving power; ability to grasp or take in impressions, ideas, knowledge'. This is certainly something more than the size of a man's head.
>
> [Box 2: report of Committee discussion on Hydrologic Terminology, p. 5, undated but, from references cited, 1943 or later]

The reference to the Soil Conservation Service (SCS) seems to have arisen because of comments received criticizing the use of the term infiltration capacity (which Horton had by then used for many years). In a letter to Mr C. E. Ramser of the SCS, Horton adds:

> The author of the statements quoted above suggests nothing better and in alleging inadequacies of the term 'infiltration capacity' he leaves the important question of making a definite distinction between infiltration at capacity rates and infiltration at lower rates which are not capacity rates, unresolved. In reading this discussion I am reminded of the adage that you can lead a horse and some other related animals to water but you can't make them think.
>
> [Box 2: copy of letter dated June 7, 1943]

Horton and the Effects of Macropores on Infiltration

Horton was thus well aware of the effects of both colloidal transport and macropores on infiltration, even though he does not appear to have used the term macropore and it does not appear in his discussion

Figure 3. Horton's sketch for figure 13 of the Infiltration of Rainfall monograph. He notes: 'Apparently the manner in which air escapes and water enters a natural or cultivated soil surface with numerous alternate depressions and summits is somewhat as shown in Figure 13. Dark areas indicate water flowing down the slopes of micro-basins or accumulated in depressions. Arrows flying upward indicate escaping air and those flying downward indicate infiltration. A, B and C are earthworm holes or other soil perforations. Water is flowing down A, while air is escaping freely from B and C, the latter forming the only outlet for air between two depressions, one of which is overflowing into the other' [Box 61: Manuscript Infiltration of Rainfall, p. 51, original drawing in pencil, with erasures]

of hydrological terminology (1942). Nor does any similar term, such as secondary porosity, preferential flow or percolines. He did, however, use the terms 'macro-structure' and 'macro-openings' (Horton, 1940). Figure 3, a rough draft in Horton's hand found in the manuscript of *Infiltration of Rainfall* [Box 61], demonstrates clearly that he was aware of the role of secondary porosity *and* surface roughness in both the infiltration of water and the escape of air. It also suggests that he thought that infiltration into macropores would require ponding and excess water to be available at the surface, while deeper into the soil the macropores would serve to provide additional surfaces for the infiltration of water into the matrix. It is strikingly similar to the schematic diagrams to be found, for example, in Dixon and Peterson (1971) and Beven and Germann (1982), 30 and 40 years later.

The manuscript of *Infiltration of Rainfall* also contains a section on *Earthworm and Root Perforations* that refers both to the American edition of Charles Darwin's *The formation of vegetable mold through the action of worms* and an extended quotation from the paper by Lawes *et al*. (1882) on rapid drainage from the lysimeters at Rothamsted in England.[6] Horton notes, however, that he did not know the latter at first hand; the quotation had been taken from an even

[6] 'It would be a mistake to regard an ordinary soil as a uniform porous mass, which simply becomes saturated with water, and then parts with its surplus by drainage; soil is, in fact, penetrated by innumerable small channels and through these more or less of the drainage always takes place. Some of these channels consist of sun-cracks, which becoming partly filled with sand and small stones, remain partially open after dry weather has ceased. The deeper channels are, however, not of this character, but are produced by the roots of plants, or to a still greater extent by the burrowing of worms. The soil drainage-gauges we are now concerned with have furnished illustrations of both these actions. During the digging of the trenches round the gauges, barley roots were observed penetrating the soils to a depth of 50 or 60 inches. When such roots decay, a small open channel is left through which drainage can take place. ... Worms have not unfrequently appeared on the collecting funnel of the 20 inch gauge, having come through the soil above, and what appear to be worm-casts, dropped from the holes of the perforated iron plates, are of still more frequent occurrence. Worms have also appeared, though much more rarely, on the collecting funnels of the 40 and 60 inch gauges. The holes made by worms thus descend to a considerable depth, and if numerous, must have an important influence on drainage' [Lawes *et al*. (1882: 275), as quoted by Horton in Box 61: Manuscript of *Infiltration of Rainfall*].

more unlikely, albeit more recent, source (Leather, 1912). Horton notes that he

> [H]as observed as many as a dozen earthworm mounds per square foot on a well sodded area. The walls of the earthworm holes under sod are protected by the matrix of roots, while their mouths are protected by the sod. They are, therefore, much more permanent than in cultivated land. In middle latitudes earthworms operate generally through the entire growing season or frost-free period. Some of the holes, especially underground passages, may persist throughout the winter, but it is probable that earthworm perforations are one of the factors which contribute to the greater infiltration capacity of the soil in summer than in winter. Earthworms prefer rich, fertile soils and do not thrive in sands. As the soil dries out they go deeper, providing facilities for deep penetration of water when most needed.
>
> [Box 61: MSS of *Infiltration of Rainfall*, pp. 37–38].

Horton, then goes on to make a calculation, based on 'the well-verified law of Poiseuille', to compare the flux rates of capillary pores with those of 0·1 to 0·2 inch (0·25 to 0·51 mm) 'earthworm perforations' (see Table II). The lines of the table are ticked where Horton had checked his calculations.

The Effects of Air on Infiltration

Horton's papers reveal that he was also concerned about the effects of entrapped air on infiltration rates.

Table II. Horton's calculations of the equivalent numbers of capillary tubes of different sizes to provide the same flux as two different sizes of macropores [Box 61: Earthworm and Root Perforations in Manuscript *Infiltration of Rainfall*]

Diameter (mm)	Diameter (inches)	Equivalent value of 0.1 inch hole	Equivalent value of 0.2 inch hole
1/400	0·0001	1 000 000 000 000	4 000 000 000 000
1/40	0·001	100 000 000	400 000 000
$\frac{1}{4}$	0·01	10 000	40 000

Horton (1940) reports on a series of laboratory experiments on infiltration into soil columns, with and without capillary tubes acting as air vents and with air pressure within the soil measured by manometer. He was also critical of others (in the SCS again) who had not been concerned with air pressure effects:

> . . .nor anywhere else in this paper is there found any mention whatever of the equally important effect of temperature on the viscosity of air in the soil, although the paper contains abundant evidence, to one whose eyes are trained to see it, that the outflow of air is an important factor in relation to infiltration-capacity.
>
> [Box 59: memo commenting on a draft of a manuscript 'Relative infiltration of certain soils' by Free, Browning and Musgrave, p. 3][7]

His experiments, in which soil was packed into a glass jar open at the top and then subjected to ponded infiltration showed clearly that allowing air to escape through the capillary tubes significantly increased the infiltration capacity of the soil. Without the tubes water was seen to bubble occasionally around the edge of the soil mass, but infiltration was lower. It does seem, however, that this was a case where there was no other pathway for air escape than through the soil surface. However, he was also aware of what might happen under natural and experimental conditions in the field:

> It should be pointed out that in most of these experiments on plats,[8] rates of application greatly exceeded those occurring from natural rainfall, and volumes of water applied were often greatly in excess of those ever occurring in a single shower or storm. As a result, the soil was wetted to a greater depth than would ever occur under natural conditions,. . . the length of flow of soil air from the downward advancing front of moisture to the surface was greatly increased, resistance of the escape of air increased, and

[8] Horton (1942: 482) notes that the term plat is to be preferred to plot noting that 'English usage, as may been seen from consulting, for example, the Oxford Dictionary, favors the word "plat" in this connection, a plat being a subdivision of the land-surface. No adequate justification for the use of the word "plot" has been offered'.

factors brought into play affecting infiltration-capacity which ordinarily have little or negligible effect under natural rainfall conditions, especially during the latter part of the runs. Also it is probable that the lateral movement of air, particularly in cases with a more or less impervious layer at some depth, is far more important in affecting infiltration-capacity than the lateral movement of water.

[Box 59: memo commenting on a draft of the paper 'Relative infiltration of certain soils' by Free, Browning and Musgrave, p. 3–4].

The Horton Infiltration Equation

It is worth noting that Horton did not introduce his infiltration equation in his classic 1933 paper. It was not until Horton (1939) that he published a predictive equation for infiltration capacity in the form

$$f = f_c + (f_o - f_e)\, e^{-K_f t} \qquad (1)$$

'where f = infiltration-capacity, inches per hour, at time t, in hours, f_o = infiltration-capacity at time $t = 0$; f_c = minimum constant infiltration capacity; K_f is constant for a given curve' (Horton, 1939: 697). Horton (1940: 399) notes that

> ... this was originally given as an empirical equation. It can, however, be derived from the simple assumption that the processes involved in the reduction of f as rain continues are of the nature of exhaustion processes. These processes include rain-packing, in-washing, breaking down of the crumb-structure of the soil, the swelling of colloids and, in cases where they occur, the closing of sun-checks.[9]

[9] He goes on to note that 'the graph of an inverse exponential equation can be represented over a considerable range by a hyperbola having the equation $f = a/t^n$. Such a hyperbolic equation or an equation derived therefrom by integration has sometimes been given. Hence it has seemed necessary to point out that such an equation, while it may quite accurately represent experimental data of an infiltration-capacity curve over a considerable range, violates the fundamental principle of curve fitting that the equation adopted should if possible fit not only the experimental data but give correct results for known conditions outside the experimental range. The above equation gives infinite infiltration-capacity for $t = 0$ and indicates that infiltration capacity approaches zero as a limit as the duration of rainfall increases, whereas, in fact, the infiltration-capacity almost invariably approaches a constant finite value, not zero' (Horton, 1940: 399). See also the similar comments of Horton about the Green–Ampt equation noted in the main text.

Horton invokes 'exhaustion processes' in the derivation of this equation by assuming that all of the processes affecting the rate of change of infiltration capacity are linearly proportional to 'the work remaining to be performed $(f - f_c)$' (Horton, 1940). Integration leads directly to the form of Equation (1), with the constant of proportionality as K_f and the constant of integration defined by $f = f_o$ at $t = 0$.

The exponential decline towards a constant value of Equation (1) results in a similar pattern of change in infiltration capacity as other infiltration equations, such as that of Green and Ampt (1911), which assumes a piston-like wetting front and a constant drop in potential across the front augmenting the gravitational component of the total gradient of potential; or the analytical equations of Philip (1957) that solve the Darcy–Richards equation for different boundary conditions and soil characteristic functions (and other more complex variants since). Horton's approach appears to neglect any consideration of the role of capillary potential gradients in the decline of infiltration capacity over time, which is perhaps why the impression has persisted that his equation was, indeed, purely an empirical equation, curve-fitted to measured data.

Horton was quite aware of this, however. He contrasts his own view of infiltration capacity as largely controlled by the surface layer, with the view that it is largely controlled by the soil mass, in which it is assumed that

> the only thing that changes during an infiltration experiment is the moisture content of the soil down to the depth of presentation... If capillary pull at the moist front within the soil was the only factor involved in the change of infiltration-capacity with time during rain, then differences in soil cover and surface treatment should have little effect in cases, where, as is often true, the depth of moisture penetration is below the depth of surface treatment. Numerous experimental data show that even in such cases where there is a marked variation of infiltration-capacity for the same soil with the same depth of penetration with different types of cover and different surface treatments.
>
> (Horton, 1940: 404).

Plots of some of his own infiltration data collected at the Horton Hydrological Laboratory (see Beven (2004a)), and that reported at the same time by Duley and Russell (1939), support this conclusion.

Thus, Horton would (and did) reject as too simple the physics-based approach to modelling infiltration based on the Darcy–Richards equation that dominates today. While today we recognize the Green–Ampt equation as a simplification of the Darcy–Richards equation, Horton criticized it for *not* being physically realistic because it predicts an infinite infiltration capacity at $t = 0$. 'This does not happen, since the velocity of entrance to the surface pores of the soil increases, velocity and entry heads, ordinarily negligible in case of infiltration, become controlling factors' [Box 62: Manuscript on *Theoretical Treatment of Infiltration*, p. 31]. He proposed a modification that avoids this implication [Box 62], but his main objection to these approaches was that they neglected the surface effects that he considered to be dominant. Certainly, there have been modern attempts to model both the surface effects and capillarity effects on infiltration capacity (e.g. Smith *et al*., 1999), but one suspects that Horton would still have found them too simple, despite his frequently expressed desire always to analyse processes in terms of fundamental hydraulic principles (see Beven (2004b)).

As evidence for his view, Horton (1940) cites the experiments of Beutner *et al*. (1940), who carried out infiltration measurements on runoff plats in Arizona. At each site an initial run was made under dry conditions, the equipment was left in place and the following day a second run was made. The results suggested that the initial infiltration capacities of the wet run were generally close to that of the dry run, that the infiltration capacity decreased more quickly in the wet soil, and that the final infiltration capacity was generally *lower* in the wet run than in the dry run. Horton argues that this must be as the result of surface packing and other near-surface processes, since if infiltration capacity was controlled by the soil mass then the initial infiltration capacity should be less and should decrease more slowly in the wet run (because capillary gradients would be less and depth of penetration was greater in the wet run). He also argues that neither experiment should reach a final infiltration capacity but should continue to decrease slowly in both cases if infiltration were controlled by the soil mass.

> Finally, bearing in mind that the soil is not, as a rule, fully saturated during infiltration under natural conditions, it is difficult to show how capillary pull at the moist front can be transmitted effectively to the soil surface so as to in any way affect or increase the infiltration-capacity in the presence of capillary surfaces exposed to air within the soil. The situation is like that of attempting to apply a suction pump under conditions where there is an air leak in the suction pipe. It does not work.
>
> (Horton, 1940: 405)

Horton does allow that

> There are probably cases to which the explanation of the changes in infiltration-capacity on the basis of conditions at and close to the soil surface does not apply, as, for example, a fat clay soil in which the principal change as a result of partial drying is the formation of deep and possibly numerous sun-checks. In such cases, aside from the possible puddling of the soil surface by the energy of falling rain, the principal factor involved in the variation of infiltration-capacity is the area of exposed surface of sun-checks and this unquestionably varies with the degree of swelling of the colloids within the soil adjacent to the walls of the sun-checks.
>
> Another case is that of a pure sand which contains no colloids, does not rain-pack and has no crumb structure. There is experimental evidence that such soils, sometimes at least, show decrease of infiltration-capacity with duration of rain.
>
> (Horton, 1940: 406).

Horton also recognizes that the experiments on infiltration capacity were affected by the nature of the experiments themselves, and gives an extended discussion of the effects of drop size on infiltration rates but suggests that there is little evidence of any increase in infiltration capacity with either rainfall intensity or drop sizes. He also suggests that rough surfaces might have lower infiltration capacities than smooth surfaces because 'if very large drops fall

on a steep sloping surface, such as the slope of a tillage mark, a part of the drop runs downward into the intermediate gully or depression and begins to build up surface detention and runoff, even at times when the soil surface is not all absorbing water at its maximum rate' (Horton, 1940: 409).

Horton as Hydrologic Modeller and the Scale Problem

The infiltration equation provided Horton with the means to make predictions of runoff volumes (at least if the changes of infiltration capacities due to soil, seasonal and land treatment effects could be estimated). Elsewhere, he treats the problem of allowing for depression storage and the hydraulics of overland flow and channel flow, including transitions from laminar to turbulent flow, in routing that runoff to the basin outlet (Horton, 1935). He realized, however, that in applying this theory he would need to deal with the fact that there might be different infiltration capacities in different parts of a basin and that this would not be a problem in prediction (he proposed a distributed approach based on the division of a basin into 'meshes' of different shapes and characteristics; Horton, 1938; see Beven (2004b)). It would, however, be a problem in the *analysis* of rainfall-runoff data in a complex basin.

The initial requirement in analysis is to effect the separation of that part of the hydrograph due to surface runoff and that due to groundwater. Horton (1933) explains how to construct the 'normal depletion curve' for a basin (more usually now called the master recession curve) by matching segments of recession curves, and how to represent the normal depletion curve by an equation of the form

$$q = q_o e^{-ct} \tag{2}$$

which he states was first derived by himself in 1904 (Horton, 1914), and independently by both Maillet and Boussinesq in 1903 (Horton, 1933: 448). He also suggests that for a large basin within which there may be many different phreatic sub-basins, a better expression might be

$$q = q_o e^{-ct^n} \tag{3}$$

Once the normal depletion curve has been derived, it can then be used to analyse observed hydrographs and separate the two components into 'rainfall-excess' and 'baseflow'.[10] Once the surface runoff component has been determined in this way, Horton then explains how it will be possible to determine the average infiltration capacity of a drainage basin. He notes that this is just one way of determining infiltration capacity. Other methods are laboratory experiments using artificial rainfall, from runoff–plat experiments using natural rainfall, and that using rainfall and runoff data will work best for small basins with homogeneous soils, whereas for a drainage basin where soil type varies the result will be the estimation of an 'average equivalent infiltration-capacity' (Horton, 1933: 480). He also expresses the hope that the accumulation of many such analyses will 'supply much-needed information as to infiltration capacities and particularly as to the characteristics of surface detention–surface runoff and channel storage–outflow relation curves' (Horton, 1935: 67).

The approach is extended in Horton (1937b) to the case where rainfall intensities on part of a basin do not rise above the infiltration capacity of the soils. He notes how there might be difficulties in estimating rainfall intensities over a large basin, and that the period of rainfall excess might begin and end at different times on different parts of the basin (Horton, 1935: 67).

These comments suggest that Horton had an early appreciation of many of the problems confronting the hydrological modeller, including temporal change in parameter values, the dependence of parameter values on scale and the necessity, faced with the complexities of the real world, of model calibration and effective parameter values. This was made explicit in a comment about the estimation of roughness coefficients:

> I would not be concerned over the fact that the values of the roughness factor n may not appear consistent provided I can duplicate the hydrographs, as I feel certain I can. The roughness factor n, especially where there is suspended matter and gullying and cross currents, is not really the same thing as Manning's n. As yet we know but little about it.

[10] Horton points out in passing that other methods of hydrograph separation suggested by Houk (1921) and in the USGS Water Supply paper of Meinzer and Stearns (1929) are incorrect and will underestimate the groundwater contribution to stream flow.

[Box 63: Comments on Borst and Woodburn's runoff plot experiments at Zainesville, OH, dated 31 May 1939]

Horton does not, however, seem to have had too many doubts about applying average infiltration capacities derived under one set of rainfall conditions to the prediction of runoff under other conditions. He did observe that there were seasonal changes in infiltration capacities derived in this way (Figure 2), and that minimum values might be more robustly estimated than maximum values (which might still underestimate the potential maximum values achievable). He suggests, however, that minimum values will be useful in the estimation of the 'maximum flood intensity' to be expected on a given area (Horton, 1937b: 385).

Conclusions

There are likely to be many other insights contained in Horton's boxes of papers; it was possible to examine only 10 of the boxes in detail in the days available. A full study of the interesting interrelationships and exchanges of ideas between Horton and other hydrologists of the time is also still outstanding, but would probably require the extended attention of a professional historian of science to access the necessary sources and do the story justice. Even this brief study, however, has been surprising, throwing light on Horton's perceptions of the complexity of processes affecting infiltration and surface runoff. It reveals an unexpected depth of process understanding in comparison with the simplistic way in which Horton's concepts of runoff generation are presented in modern hydrological textbooks. It is not that modern texts are inconsistent with Horton's methods of analysis; he did, after all, persist with the idea of the soil as a separating surface, despite the concurrent arguments for subsurface contributions to the hydrograph made by Hursh and Brater (1941; Hursh, 1944). But then most hydrologists (with some notable exceptions) essentially retained the perception of storm runoff as rainfall excess until the demonstration of large contributions of 'old' water to the storm hydrograph by Sklash and Farvolden (1979), and there are many rainfall-runoff models that retain the concept as the sole mechanism of runoff generation still.

So, it is perhaps his persistence with the equivalence of rainfall excess with storm runoff that is most surprising, given Horton's sophisticated appreciation of the complex processes involved at the soil surface (and evidence from analyses of his own storm runoff and infiltration data at the Horton Hydrological Laboratory; see Beven (2004a)). There would appear to be two possible explanations. The first is that he simply could not believe that subsurface flows could be fast enough to contribute to the hydrograph. This is supported elsewhere when he rejects a suggestion that 'wave translation' could be a mechanism for subsurface contributions to the hydrograph, but he also cites evidence for cases of rapid rises of groundwater prior to peak stream changes (see the discussion in Beven (2004b)). The second is that perhaps, in the end, the pragmatic constraints of what was possible in practical applications for a 'Consulting Hydraulic Engineer' were sufficient to dominate the perceptual understanding of a hydrological scientist. We would not now agree with all of Horton's perceptual model of infiltration processes, but his appreciation of the real nature of surface controls on infiltration capacities raises the question as to whether we have really significantly advanced our understanding in the last 60 years, or whether we have, as suggested by Klemeš (1986), lost something through overenthusiastic 'mathematistry'.

References

Beutner EL, Gaebe RR, Horton RE. 1940. Sprinkled-plat, runoff, and infiltration experiments on Arizona desert soils. *Transactions, American Geophysical Union* **21**: 550–558.

Beven KJ. 2004a. Infiltration excess overland flow at the Horton Hydrological Laboratory (or not?). *Journal of Hydrology* **293**: 219–234.

Beven KJ. 2004b. Robert E. Horton and abrupt rises of groundwater. *Hydrological Processes* **18**: in press.

Beven KJ, Germann PF. 1982. Macropores and water flow in soils. *Water Resources Research* **18**(5): 303–325.

Brutsaert W. 1993. Horton, pipe hydraulics and the atmospheric boundary layer. *Bulletin of the American Meteorological Society* **74**: 1131–1139.

Cook HL. 1946. The infiltration approach to the calculation of surface runoff. *Transactions, American Geophysical Union* **27**: 726–747.

Dixon RM, Peterson AE. 1971. Water infiltration control: a channel system concept. *Soil Science Society of American Proceedings* **35**: 968–973.

Dooge JCI. 1992. Sensitivity of runoff to climate change—a Hortonian approach. *Bulletin of the American Meteorological Society* **73**: 2013–2024.

Duley FL, Russell JC. 1939. The use of crop residues for soil and moisture conservation. *Journal of the American Society of Agronomy* **31**: 703–709.

Free GR, Browning GM, Musgrave GW. 1940. *Relative infiltration and related physical characteristics of certain soils*. USDA Technical Bulletin 729, Washington, DC.

Green WH, Ampt G. 1911. Studies of soil physics. Part 1. The flow of air and water through soils. *Journal of the Agricultural Society* **4**: 1–24.

Hall FR. 1987. *Contributions of Robert E. Horton*. AGU Monograph on the History of Geophysics, vol. 3. American Geophysical Union: Washington, DC; 113–117.

Hornberger GM, Raffensperger JP, Wiberg PL, Eshleman KN. 1998. *Elements of Physical Hydrology*. Johns Hopkins University Press: Baltimore, MD.

Horton RE. 1914. Discussion on yield of drainage-areas. *Journal of the New England Water Works Association* **28**(4): 538–539.

Horton RE. 1933. The role of infiltration in the hydrologic cycle. *Transactions, American Geophysical Union* **14**: 446–460.

Horton RE. 1935. *Surface Runoff Phenomena. Part 1. Analysis of the Hydrograph*. Horton Hydrologic Laboratory Publication 101. Edward Bros: Ann Arbor, MI.

Horton RE. 1936a. Hydrologic inter-relations of water and soils. *Proceedings of the Soil Science Society of America* **1**: 401–429.

Horton RE. 1936b. Maximum groundwater levels. *Transactions, American Geophysical Union* **17**: 344–357.

Horton RE. 1937a. Hydrologic aspects of the problem of stabilising stream flow. *Journal of Forestry* **35**(11): 1015–1027.

Horton RE. 1937b. Determination of infiltration-capacity for large drainage basins. *Transactions, American Geophysical Union* **18**: 371–385.

Horton RE. 1938. The interpretation and application of runoff experiments with reference to soil erosion. *Proceedings of the Soil Science Society of America* **3**: 340–349.

Horton RE. 1939. Analysis of runoff-plat experiments with varying infiltration capacity. *Transactions, American Geophysical Union* **20**: 693–711.

Horton RE. 1940. An approach towards physical interpretation of infiltration capacity. *Proceedings of the Soil Science Society of America* **5**: 399–417.

Horton RE. 1942. Remarks on hydrologic terminology. *Transactions, American Geophysical Union* **23**: 479–482.

Horton RE. 1945a. Erosional development of streams and their drainage basins: hydrophysical to quantitative morphology. *Bulletin of the Geological Society of America* **56**: 275–370.

Horton RE. 1945b. Infiltration and runoff during the snow-melting season, with forest-cover. *Transactions, American Geophysical Union* **26**: 59–68.

Houk. 1921. *Rainfall and runoff in the Miami Valley*. Miami Conservancy District Technical Reports, Part 8, Dayton, OH.

Hursh CR. 1944. Subsurface-flow. *Transactions, American Geophysical Union* **25**: 743–746.

Hursh CR, Brater EF. 1941. Separating storm-hydrographs from small drainage-areas into surface- and subsurface-flow. *Transactions, American Geophysical Union* **22**: 863–871.

Kirkby MJ, Chorley RJ. 1967. Throughflow, overland flow and erosion. *Bulletin of the International Association of Hydrological Scientists* **12**(3): 5–21.

Klemeš V. 1986. Dilettantism in hydrology: transition or destiny. *Water Resources Research* **22**(9): 177s–188s.

Lawes JB, Gilbert JH, Warington R. 1882. On the amount and composition of the rain and drainage water collected at Rothamsted. *Journal of the Royal Agricultural Society of England* **18**: 2–71.

Leather JW, Walter. 1912. Memoirs of the Department of Agriculture in India, Records of Drainage in India. *Agricultural Research Institute of Pusa; Chemistry Series* **II**(2): 110.

Linsley RK, Kohler MA, Paulhus JLH. 1949. *Applied Hydrology*, 1st edition. McGraw-Hill: New York.

Linsley RK, Kohler MA, Paulhus JLH. 1982. *Hydrology for Engineers*, 3rd edition. McGraw-Hill: New York.

Meinzer OE. 1942. *Hydrology*. McGraw-Hill: New York.

Meinzer OE, Stearns ND. 1929. A study of groundwater in the Pomeraug Basin, Connecticut: with special reference to intake and discharge. *United States, Geological Survey*, Water Supply Paper **597-B**.

Philip JR. 1957. The theory of infiltration. 1. The infiltration equation and its solution. *Soil Science* **83**: 345–357.

Sherman LK. 1932. Streamflow from rainfall by unit-graph method. *Engineering News Record* **108**: 501–505.

Sklash MG, Farvolden RN. 1979. The role of groundwater in storm runoff. *Journal of Hydrology* **43**: 45–65.

Smith RE, Corradini C, Melone F. 1999. A conceptual model for infiltration and redistribution in crusted soils. *Water Resources Research* **35**: 1385–1393.

USACE. 1997. Water Resources: Hydraulics and Hydrology—Interview with Franklin F. Snyder, Publication Number: EP 870-1-54. http://www.usace.army.mil/inet/usace-docs/eng-pamphlets/ep870-1-54/ (accessed 1 October 2004).