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Long-term changes in stream bank soil pipes and the effects of afforestation

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[1] Natural soil pipes are now recognized as potentially significant elements in hillslope drainage systems, sometimes developing into open channel tributaries or contributing often substantial volumes of quick flow to streams. However, there has been no detailed, long-term monitoring study of the evolution of pipe networks to indicate how permanent they are or how readily they may develop into open channels. This paper reports a resurvey of a section of stream bank in the English Peak District and compares it with the original survey 35 years previous. Comparison of the distribution, size, and shape of pipes on both banks of a 250 m stretch of the stream reveals significant changes. There were no cases of roof collapse forming new open channels. However, there has been a significant change in land use within the basin, with afforestation of the east bank. The resurvey shows a marked reduction in the number and size of pipes on the forested bank, but no significant change on the opposite bank that has remained moorland. The number of pipe outlets on the afforested bank halved over the period, and their mean diameter has reduced by 30%. In combination with the reduced number the smaller size resulted in a 71% reduction in the total area of stream bank occupied by pipe outlets on the forested bank. It is postulated that the change is primarily due to a change in the amount of throughflow beneath the forest caused by an increase in evapotranspiration.

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1. Introduction

[2] Natural soil piping has been shown to be a widespread feature of the British uplands [e.g., *Jones et al.*, 1997; *Holden*, 2005]. It is also present in most climatic zones of the world [e.g., *Bryan and Jones*, 1997; *Jones*, 2004] and has been linked to accelerated soil erosion [e.g., *Newman and Phillips*, 1957; *Jones*, 1997a; *Beckedahl*, 1998] and flood generation [e.g., *McCaskill*, 1973; *Jones*, 1997b]. Hydrological experiments in the Cambrian Mountains of mid-Wales have indicated that almost 50% of streamflow is derived from soil pipe discharge during storms [*Jones and Crane*, 1984; *Jones*, 1987a].

[3] Despite speculation on the long-term evolution of soil pipe networks, including suggestions that they can form the foci for stream channel extension [*Jones*, 1971], no long-term monitoring or resurvey studies have been published that might either confirm or deny such hypotheses. The evidence for stream channel extension comes mainly from short-term observations of processes in action, for example, by *Jones* [1968] in Arizona, *Aghassy* [1973] in Israel, or *Galarowski* [1976] in Poland, or from static observations of channel form, especially from cases of partially collapsed roofs and bridged sections of channel in Britain [*Jones*, 1987b, 1990]. A few authors have speculated on the time-scales of piping life cycles, but without direct observations of these cycles. *Jones* [1968] suggested that cycles lasted 20 years in the San Pedro valley, Arizona, leaving extended arroyos. *Galarowski* [1976] suggested that cycles lasted 10 years in the East Carpathians, based on personal information from Starkel, who believed that valley development in the area was caused by progressive "suffusion" [*Starkel*, 1960], an East European term for subsurface erosion often applied specifically to piping processes [*Jones*, 1981, p. 8].

[4] More recently, *Zhu* [2003] conducted a medium-term monitoring program on tunnel or pipe development in the Loess Plateau of Northern China over a 12 year period from 1989 to 2001. He found that there was rapid but spasmodic development, with a doubling in the number of tunnel inlets, mostly initiated during catastrophic storms. Sixty-seven of the 97 new inlets were initiated in the last two years, almost all during one storm in 2000 which delivered 107 mm in 7.5 h and had a 50-year return period. *Zhu* [2003] compared tunnel parameters with the geometry of the British pipe networks in the Maesnant catchment in mid-Wales, reported by *Jones* [1987a] and *Jones et al.* [1997]. While the volumetric intensity of tunnels was far greater in the highly erodible Lishi Loess at Yangdaogou (224 277 m^3/km^2 against only 260.3 m^3/km^2 in the Welsh basin), the density of tunnels was greater in the stagnopodzols (aquods) and oligo-amorphous peat (histosol) in

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Maesnant (14.10 km/km^2 against only 4.58 km/km^2 in the Chinese loess). In other words, the loess tunnels were fewer or shorter but they were larger than the British ones, typically 1–2 m in diameter compared with averages of 240 mm for the larger perennially flowing pipes and 93 mm for the ephemerals on Maesnant. There was also a difference in flow regime. The loess tunnels only flowed during storms; there were no perennially flowing pipes fed by groundwater. Tunnel enlargement occurred during lesser storms, but tunnel initiation and most of the erosion occurred in extreme events. Consequently, whereas the British and Chinese examples both contributed similar proportions of the total basin discharge (49% and 43% respectively), the Maesnant pipes delivered only around 15% of total sediment yield in the basin and the Yangdaogou tunnels delivered 57%.

[5] *Holden* [2006] has also studied temporal changes in pipe networks in blanket peats associated with artificial land drainage. He concludes that the density of piping along the ditches increases with the age of ditching or “gripping.” Holden’s findings can be explained by the fact that the ditches increase the local hydraulic gradient perpendicular to the side of the ditch, similar to Terzaghi’s classic formulation of pipe initiation [*Terzaghi*, 1943; *Jones*, 1981]. Holden based his conclusions on comparison of a number of peat bogs that had been drained at different times, rather than following changes at the same sites.

[6] The present paper analyzes the changes in stream bank soil pipes along the same reach of the Burbage Brook in the English Peak District, which was the site of the first published survey of stream bank soil piping in the UK [*Jones*, 1971]. It is based on two field surveys, in 1968 and 2003, separated by an interval of 35 years (Figures 1 and 2). *Jones* [1971] speculated that the pipes could exist in quasi-equilibrium with the stream network, implying that there would be little change unless the stream channel were rejuvenated by a change in base level, by an extreme hydrological event or a change in water balance. At the same time, *Jones* [1971] reported an instance of a west bank tributary of the Brook that clearly derived from a soil pipe in which the roof has largely collapsed. The latter case was more fully illustrated by *Jones* [1981]. *Jones* [1997a] also described this case, together with a similar example of almost complete roof collapse, with just a few soil bridges remaining, in the Maesnant basin in mid-Wales.

2. Site

[7] The Burbage Brook is a tributary of the River Derwent in Derbyshire, England. The original survey covered 1.5 km of the 2.5 km section of the Brook between the bridge on the A625 road at Toad’s Mouth (UK Ordnance Survey grid reference SK262807) and the bridge on the country road at grid reference SK261830 (Figure 1). The 2003 resurvey covered 250 m in the middle of this section lying in OS grid square SK2681 (latitude 53°19′ N, longitude 1°36′ E), with a mean altitude of 330 m. Including both banks, a total of 0.5 km of stream bank was resurveyed.

[8] A significant land use change occurred between the two surveys in this particular stretch of the stream. Whereas the west bank has remained open moorland pasture, between autumn 1968 and spring 1970 the east bank was planted with coniferous trees – Scots pine, Japanese larch, and Lodgepole pine. The plantation has never been commercially managed or thinned (N. Selwood, personal communication, 2003).

[9] In the 1960s, the catchment was maintained as an experimental basin by the Trent River Authority. The stream gauge is still maintained by the Authority’s private successor, Severn Trent Water, which reports to the National Water Archive. The stream originates in Ringinglow Bog in the Peak District National Park, 10 km west-southwest of Sheffield, toward the southern end of the Pennine mountain range (Figure 1). The Bog is an expanse of blanket bog with low gradient rising to 451.0 m above mean sea level and resting on top of the Carboniferous Millstone Grit scarp. The Millstone Grit forms the eastern edge of the denuded anticline of the Pennines. The peat covers 42.4% of the basin and reaches up to 10 m in thickness (Centre for Ecology and Hydrology, National River Flow Archive, http://www.ceh.ac.uk/data/nrfa/index.html, accessed 2006, hereinafter referred to as CEH, 2006). Although there are pipes at a number of levels in the deep peat, similar to those described by *Holden and Burt* [2002] in the Little Dodgen Pot Sike (LDPS) catchment in the Moor House National Nature Reserve in the Northern Pennines, the main area of stream bank piping begins once the Brook has crossed the gritstone edge, formed by the Middle Grit at 430 m above sea level, and flows across the fractured Carboniferous Middle Shales, which are partly covered by shallow solifluxion “head” deposits, 1–2 m thick [*Said*, 1969]. This valley section forms roughly two thirds of the basin and is locally known as a “clough.” Here the stream bank soils are classified as humod according to the USDA soil taxonomy [*Soil Survey Staff*, 1975] or the humo-ferric podzol subgroup, Anglezarke association, according to the Soil Survey of England and Wales [*Avery*, 1980; *Rudeforth*, 1997]. The degree of podzolization varies and many soils in the lower section of the stream in Figure 1 may best be described as lessivé brown earths, displaying the first signs of podzolization, accompanied by the occasional groundwater gley. The banks are typically around 1.0 m high, with the lower decimeters comprising clay with shale fragments or occasional shale bedrock.

[10] The hydrogeology is characterized by a moderate intergranular permeability throughout the basin. Current land use cover in the basin is 62.1% heathland and bog, 25.1% grassland and 12.7% woodland (CEH, 2006). There was no woodland at the time of the original survey in 1968.

[11] The mean annual rainfall over the period 1961–2003 is 1018 mm, or 1004 mm over the standard climatological period 1961–1990, according to data in the National Water Archive (CEH, 2006). Data from the National Archive shows that there has been no significant change in rainfall between the two surveys: the data plotted in Figure 3 indicate a mean of 983.6 mm in the 1960s compared with 1019.4 in the 10 years prior to 2003. According to *Bloomer* [1967], rainfall was 942 mm at the weir at the lower end of the experimental basin just below Toad’s Mouth (at grid reference SK 259804) and 1018 mm on Ringinglow Bog, based on rainfall records at up to 6 rain gauges in the basin from 1925 to the 1960s. Current maps in the National Archive show values of less than 950 mm at the weir with the 1000 mm isohyet almost exactly bisecting the catch-

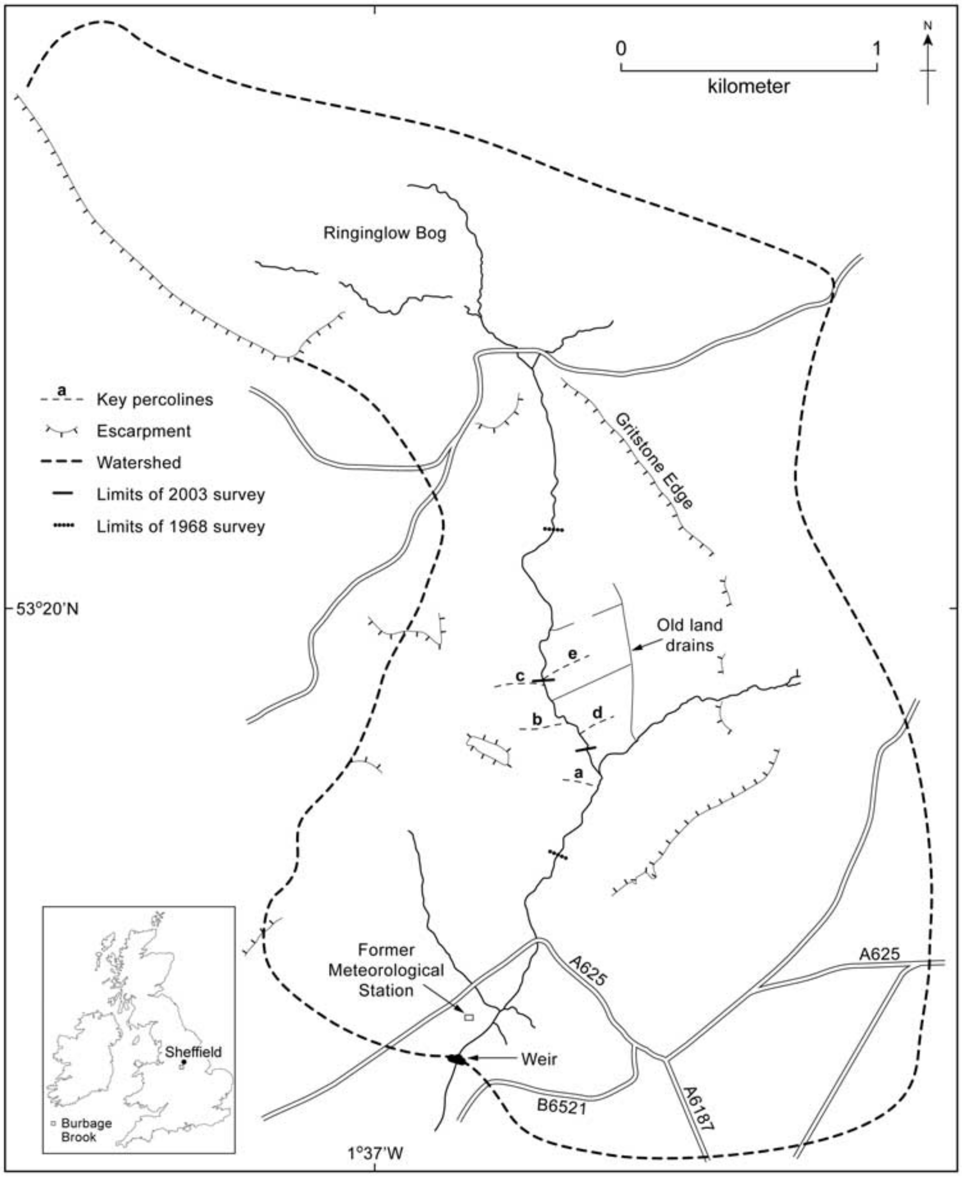

Figure 1. General location map of the study area.

ment, near the section of the stream resurveyed in 2003 (CEH, 2006). Occasional, highly localized convective storms can generate exceptional discharges, like the one in September 1931 that generated 1.4 $m^3/s/km^2$. The National Archive currently indicates a mean stream discharge of 0.17 m^3/s, a Q95 of 0.025 m^3/s and a Q10 of 0.36 m^3/s at the weir. According to the *Trent River Authority* [1966] the estimated mean daily discharge then was 0.092 m^3/s. This is for a catchment area of 9.1 km^2 above the weir and stream gauge at an altitude of 290.0 m (OS grid reference SK 259804). The weighted mean elevation in the basin is 386.8 m. Discharges are described as natural to within 10% at the 95 percentile flow.

[12] *Bloomer* [1967] calculated mean annual potential evapotranspiration as 554 mm. The period of soil moisture deficit typically extends from April to October and reaches a maximum soil moisture deficit of 40 mm, according to measurements from Howden Dam, 13 km northeast [*Trent*

Figure 2. Natural soil pipe outlets in the banks of the Burbage Brook.

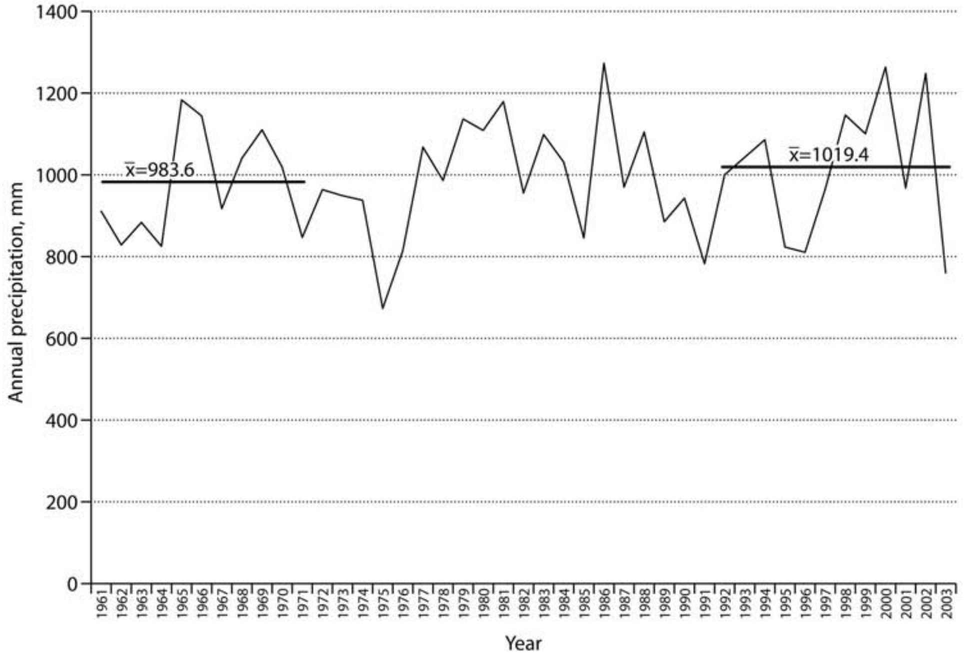

Figure 3. Rainfall time series for the Burbage basin.

River Authority, 1966]. Evapotranspiration is no longer measured on site, but values culled from the National Riverflow Archive (CEH, 2006) indicate values today similar to *Bloomer*'s [1967] estimate. The Hydrological Review for 2003 suggests potential evapotranspiration of 550–600 mm and actual evapotranspiration of 530–565 mm based on MORECS, the Met Office Rainfall and Evaporation Calculation System (CEH, 2006). While the woodland plantation is not sufficiently extensive to have had a material effect upon mean discharge at the weir, it is concentrated around the reach resurveyed in 2003 and may well have had a larger impact on lateral inflows from the hillslopes in that section of the stream.

3. Methods

[13] The resurvey used identical methods to the original. The observer walked along the streambed in waders looking for pipe outlets in the bank and measuring distance along the bank with a surveyors' tape measure. The vertical and horizontal diameters of each pipe outlet were measured by steel rule to the nearest 5 mm, together with the height of stream bank and the height of the base of the pipe above the streambed. Five millimeters was also taken as the smallest diameter for a recorded pipe, ignoring smaller macropores. The steel tape measure was used to record the depth to which the pipe could be easily penetrated. This helped to determine whether the hole was a true pipe or just an indentation caused by the loss of a large clast; it was not a measure of the length of pipe as pipes can be very sinuous over short distances [cf. *Terajima et al.*, 2000]. Water levels were also noted, together with any special features like rock outcrops, desiccation cracks or unusual soil horizons.

[14] For analytical purposes, "pipe frequency" was defined as the number of pipe outlets per kilometer of stream bank, and "pipe density" is based on the total area of bank occupied by pipe outlets, in square meters per kilometer.

[15] The shape of the pipe cross sections reflects the interaction between the erosivity of pipe flows and the erodibility of the soils. In the analyses, pipes were classified as horizontally lenticular or vertically lenticular if the relevant axis exceeded the other by more than 5 mm. Pipes were designated "circular" if neither principal axis was more than 5 mm greater than the other. Vertically elongated cross sections suggest active downcutting, whereas horizontally elongated outlets suggest that, although active erosion is occurring, pipe bed scour is being inhibited by a less erodible soil horizon. Earlier analyses at Burbage Brook indicated that the less erodible layer is typically a clay-enriched B_t horizon formed by illuviation of clays from the upper soil profile, often accompanied by the precipitation of sesquioxides [*Jones*, 1971, 1981]. Circular pipe cross sections may indicate formation by Terzaghi's "boiling" process [*Terzaghi*, 1943; *Terzaghi and Peck*, 1966] below the phreatic surface. This involves soil particles being winnowed away at the outfall.by the pressure of seeping water exceeding the unit weight of the soil particles or aggregates. The resulting depression causes a bending of the isopiestic lines and focuses flow lines on the depression, causing more rapid erosion. By analogy, caves with circular cross sections are generally regarded as being formed within the phreatic zone. Circular outlets may also indicate early development [*Jones*, 1981, p. 116].

4. Results of the Resurvey

[16] The results of the resurvey summarized in Table 1 show that there has been a marked reduction in piping within the section. There is an overall decline in the number of pipe outlets from 67 in 1968 to just 42 in 2003 (Figure 4). One-sample χ^2 tests indicate that this decline in pipe

Table 1. Comparison of Pipe Attributes Between 1968 and 2003

	Number of Pipes	Mean Diameter of Pipes, mm	Percent Change in Mean Diameter	Mean Area of Pipes, mm^2	Percent Change in Mean Area	Total Area of Pipe Outlets, mm^2	Percent Change in Total Area	Density of Piping, m^2/km	Percent Change in Density	Pipe Frequency, per km	Percent Change in Frequency
East Bank											
1968	47	101.6		10 001.7		470 080		1.8803		188	
2003	23	71.6	−30%	5917.0	−41%	136 090	−71%	0.5443	−71%	92	−51%
Significance	0.01[a]	0.005		0.005						0.001[a]	
West Bank											
1968	20	72.3		5751.8		115 036		0.4601		80	
2003	19	70.5	−2%	6134.4	+7%	116 553	+1%	0.4662	+1%	76	−0.5%
Significance	NS[a]	NS		NS						NS[a]	
Complete Reach (Both Banks Combined)											
1968	67	92.9		8733.1		585 116		2.3405		268	
2003	42	71.1	−23%	6015.3	−31%	259 319	−56%	1.0373	−56%	168	−37%
Significance	0.02[a]	0.01		0.01						0.001[a]	

[a] The χ^2 one-sample test; others by Mann-Whitney *U* test.

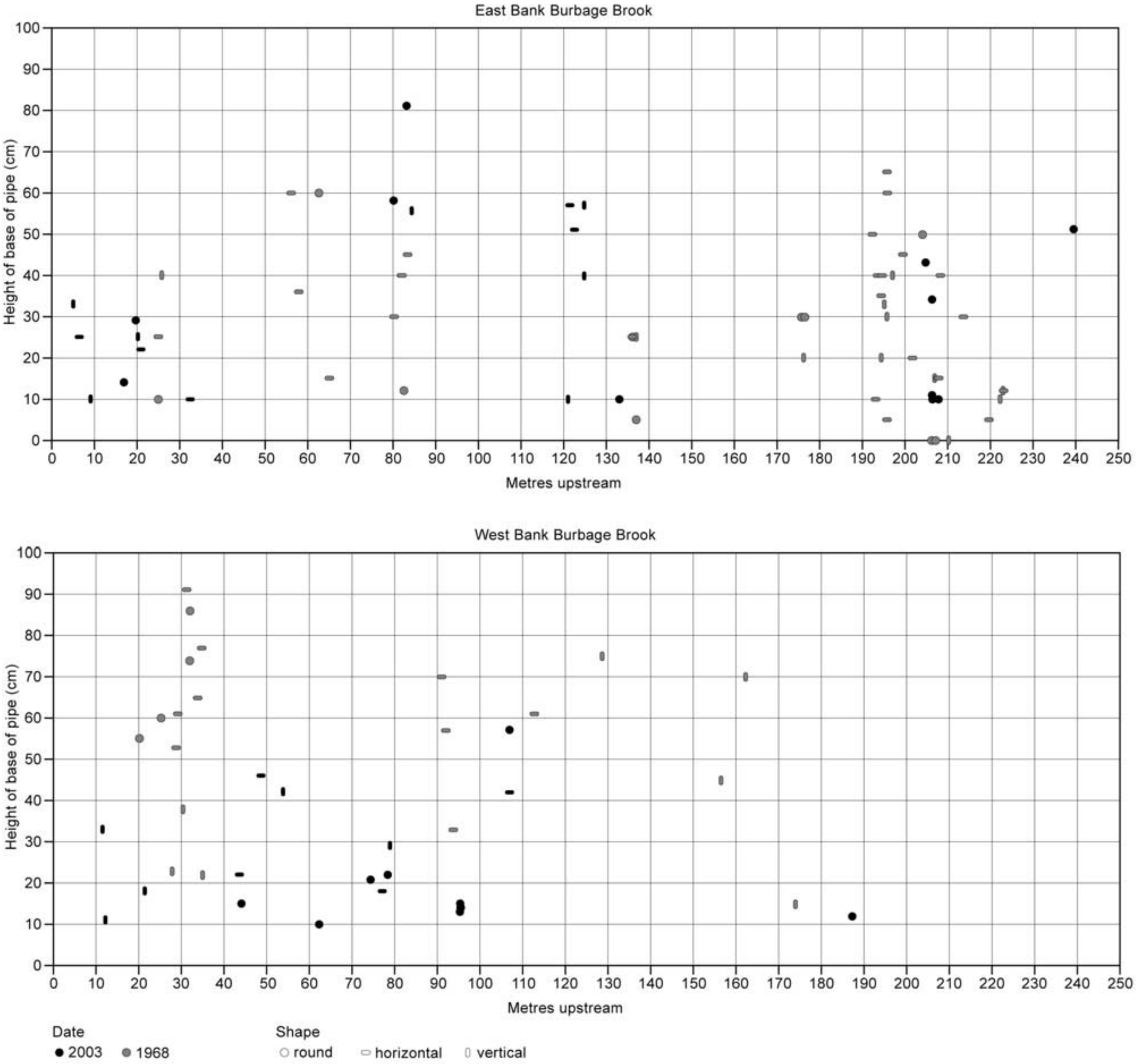

Figure 4. Comparison of pipe distributions in 1968 and 2003: (top) east bank and (bottom) west bank.

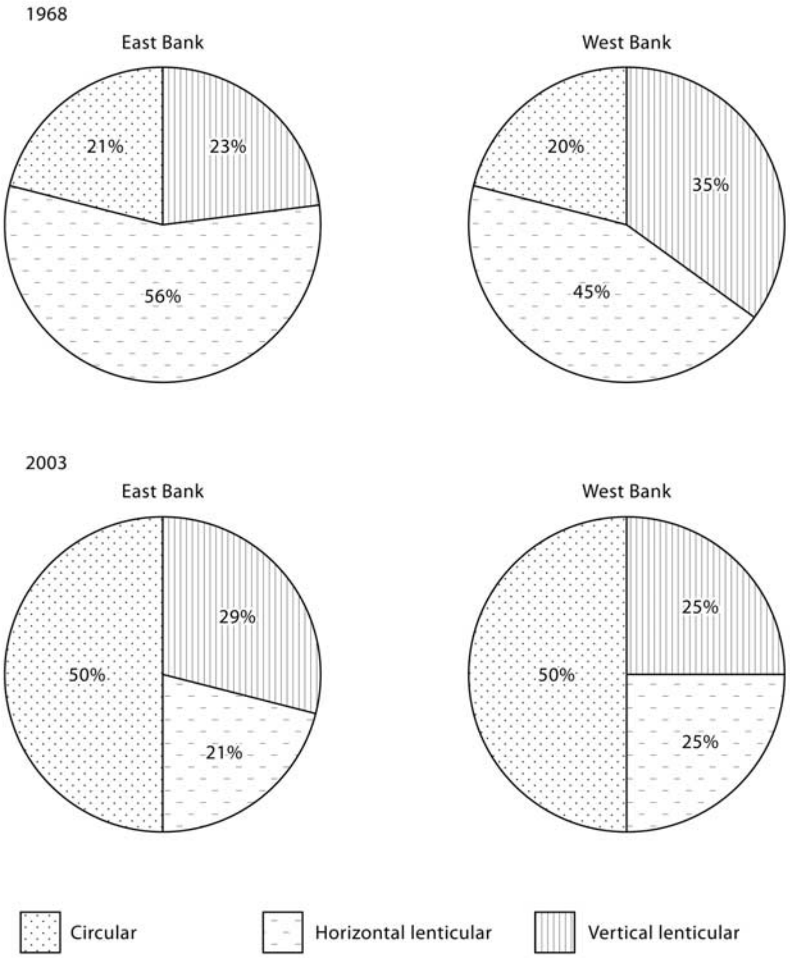

Figure 5. Changes in the proportion of pipe outfalls in different shape categories between 1968 and 2003.

numbers is significant at the 2% level and the decline in the calculated frequency per kilometer is significant at the 0.1% level. There is a 23% reduction on the mean diameter of pipes, a 31% reduction in the mean area of pipe outlets, a 56% decline in the total area of pipe outlets in the banks and a 56% decline in the calculated density of piping per kilometer of stream bank.

[17] Closer inspection reveals that this is entirely due to what has happened on the east bank where the afforestation has taken place. The number of pipe outlets on the east bank has halved since 1968, while there is no overall change in the numbers on the west bank. Chi-square tests indicate that the reductions in both the number of pipes on the east bank and the frequency of pipes per kilometer are significant at the 0.01 level and the 0.001 level, respectively.

[18] The changes in the frequency of pipe outlets are largely reflected in the size of pipes and the density of outlets, measured in square meters of pipe cross-sectional area per kilometer length of stream bank, on the two banks. There is little reportable change on the western, moorland bank in terms of the mean diameter of pipe outlets, their mean area, the total area of pipe outlets in the surveyed section or the calculated density of piping per kilometer of bank. In strong contrast, the afforested bank shows very marked reductions in all these attributes: diameter −30%, mean area −41%, total area −71% and density −71%.

[19] There have also been some marked changes in the shape of pipes. In the original 1968 survey of 138 pipe outlets on Burbage Brook, circular pipes had the lowest mean diameter (75 mm, compared with 115 mm for vertically lenticular outlets). As a result of active downcutting, the vertical outlets also formed the lowest placed group in the banks with pipe beds having a mean elevation of just 34% bankfull height against 44% for circular pipes [*Jones*, 1981, p. 117].

[20] The pie diagrams in Figure 5 show that the two banks are now very similar in terms of the distribution of shapes between vertically elongated pipes, round pipes and horizontally elongated pipes, whereas in 1968 they were very different. Now half of all the pipes on both banks are round and the remainder are almost equally divided between vertical and horizontal. Back in 1968, however, the proportions were more diverse. Horizontally lenticular pipes dominated on both banks, but more so on the east bank (accounting for 56% of pipes, against 45% on the west bank). Only about a fifth of all pipes on both banks were round.

[21] Table 2 shows large changes in the total area of outlets amongst all three categories, but these changes are

Table 2. Breakdown by Pipe Shape

	Number of Pipes	Mean Diameter of Pipes, mm	Percent Change in Diameter	Mean Area of Pipes, mm^2	Percent Change in Mean Area	Total Area of Pipe Outlets, mm^2	Percent Change in Total Area
				Vertically Lenticular			
East bank							
1968	11	105.0		10 726.0		117 986	
2003	7	97.9	−7%	10 695.4	−0.3%	74 868	−36.5%
Significance	NS[a]	NS		NS			
West bank							
1968	7	102.1		9384.1		65 689	
2003	5	94.0	−8%	8089.6	−14%	40 448	−38%
Significance	NS[a]	NS		NS			
				Circular			
East bank							
1968	10	89.2		9943.1		99,431	
2003	12	67.5	−24%	4712.5	−53%	56 549	−43%
Significance	NS[a]	NS		NS			
West bank							
1968	4	62.5		3887.7		15 551	
2003	10	60.0	−4%	6000.4	+54%	60 004	+286%
Significance	NS[a]	NS		NS			
				Horizontally Lenticular			
East bank							
1968	27	106.2		9357.9		252 663	
2003	5	50.0	−53%	2207.0	−24%	11 035	−96%
Significance	0.001[a]	0.05		0.05			
West bank							
1968	9	66.1		3755.2		33 797	
2003	5	58.0	−12%	3283.0	−12.5%	16 415	−51%
Significance	NS[a]	NS		NS			

[a] The χ^2 one-sample test; others by Mann-Whitney *U* test.

not all unidirectional: there has been approximately a one-third reduction in the total area of vertical pipes on both banks, reductions in the areas of horizontal pipes by $\sim$100% on the east bank and 50% on the west, but conflicting trends in circular pipes, a 40% reduction in area on the east bank compared with almost a threefold increase on the west.

[22] In many of these comparisons, the small numbers of pipes involved when the sample is divided into these shape categories mean that care must be taken in interpreting these changes. However, the most notable change is in the number and size of horizontal pipes on the east bank, falling from 27 to just 5 (significant at the 0.001 level by one-sample χ^2), while there are only 4 fewer horizontal pipes on the west side (not significant).

[23] If the combined number of vertically and horizontally lenticular outlets is taken as an index of overall levels of erosive activity, in 1968 there were 38 such pipes on the east bank and 16 on the west, whereas in 2003 they numbered 12 and 10 respectively. One-sample χ^2 tests indicate a highly significant reduction in erosive activity on the east bank ($p < 0.001$) and a nonsignificant reduction in the west bank.

[24] Further analysis of the size of this combined group of actively eroding pipes indicates that there was a reduction in the mean area of these outlets on the east bank from

Table 3. Heights of Pipes in the Stream Bank

			Mean Percentage Bankfull Height of Pipes			
	Mean Height of Pipe Bed, cm	Mean Height of Bank, cm	All Pipes	Vertically Lenticular	Circular	Horizontally Lenticular
East bank						
1968	28.2	78.5	35.4	28.4	30.7	40.1
2003	33.3	75.1	44.6	44.9	42.7	44.9
Significance[a]	NS	NS	0.05	NS	NS	NS
West bank						
1968	56.6	100.6	55.0	41.5	63.8	61.6
2003	24.2	65.7	35.5	38.1	31.3	41.4
Significance[a]	0.001	0.001	NS	NS	0.05	0.02

[a] Mann-Whitney *U* test.

Table 4. Spacing of Pipes Along the Stream Banks

	Nearest Neighbor Index[a]	Mean Distance Between Pipes, m	Mean Number of Pipes per Cluster	Mean Distance Between Pipes in Clusters, m
East bank				
1968	0.130	4.75	4.7	0.88
2003	0.249	12.99	2.4	1.39
Significance[b]		0.01	NS	NS
West bank				
1968	0.155	8.69	2.0	1.09
2003	0.269	15.45	1.9	0.56
Significance[b]		NS	NS	NS

[a] Zero indicates perfect clustering (all in one place), 1.0 is the random expectation, and 2.15 is perfectly regular.

[b] Mann-Whitney *U* test.

45,239 mm^2 to just 7158.5 mm^2 over the years, which is significant at the 0.025 level.

[25] Analyses of the average height of pipe outlets in the stream banks also show some significant changes. Table 3 shows that the east bank pipes are generally slightly higher in the bank in 2003 than they were in 1968. This applies to every shape of pipe, although only the figures for the percentage bankfull height of the total ensemble are statistically significant. In contrast, the west bank pipes were generally lower in the bank in 2003 than they were in 1968 in both absolute and relative terms. The absolute height of pipes has halved ($p < 0.001$) and the mean percentage bankfull heights of both round and horizontal outlets are significantly lower ($p < 0.05$ and 0.02 respectively). The overall height of the west bank itself has also been significantly lowered ($p < 0.001$), whereas there has been no change in bank height on the east bank. All these results would be consistent with continued erosion on the west bank and an attenuation of erosion on the east bank.

[26] One final aspect of pattern remains: the spatial distribution of pipe outlets *along* the banks. Tests on the full 3 km long 1968 survey data showed significant clustering in the distribution of the pipes [*Jones*, 1971]. The larger pipes tended to be found in clusters rather than individually, with 77% of above-average sized pipes occurring in clusters. Each cluster tended to have one or two "master pipes" that were much larger than the rest [*Jones*, 1981, p. 134]. A contingency test showed that there was a significant association between these clusters and the location of wetter areas of stream bank around the outfall of percolines or seepage lines. As defined by *Bunting* [1961], percolines are lines of deeper soil running downslope and forming preferred pathways for subsurface drainage; they may form "seepage lines" when and where the phreatic surface intersects the land surface causing effluent seepage (return flow) and saturation overland flow.

[27] The clustering pattern is still present (Figure 4). Table 4 confirms this, but also suggests that the clustering is less intense than it used to be. The nearest neighbor index has increased slightly on both banks. So too has the mean distance between pipes and the mean distance between pipes within each cluster, although the low number of clusters and high variability mean that these are not statistically significant, with the notable exception of the increase in the mean distance between pipes on the east bank ($p < 0.01$). Two new, but small pipe clusters have developed on the east bank, around 10–20 m upstream and 120–130 m upstream of the footbridge. However, the old clusters around 80 m and 200 m have declined, the latter from over 20 down to just five pipe outlets. No evidence of these earlier pipes remains and they have presumably been infilled by soil creep in the absence of the scouring action of pipe flow.

[28] One intriguing feature of the 1968 pattern is the imbalance between pipe densities on the two banks of the stream, which has now disappeared. The data in Table 1 show that there were significantly more pipes on the east bank than on the opposite bank in 1968 ($p < 0.001$ by χ^2), even though the land use was the same on both banks, whereas there was no significant difference in 2003. The pipes on the east bank were also larger than those on the west in 1968: mean diameters were 41% larger and mean areas 74% larger. Taken together, the larger numbers and size resulted in the total area of pipe outlets in the resurveyed reach being over 300% greater on the east bank ($p < 0.001$ by Mann-Whitney) and the same contrast in the density of pipes. None of these parameters show any significant differences in the 2003 survey.

5. Discussion

[29] Over the 35 year period the pipes in the banks of the Burbage Brook have changed significantly in size, shape, number and distribution. Overall size has reduced, but this is mainly due to a dramatic reduction in the size of pipe outlets on the east bank where afforestation has taken place. Since the internal gradient of the stream bank pipes does not appear to have increased, the reduction in cross-sectional area suggests that the overall discharge capacity of the east bank pipes has been reduced by over two thirds since afforestation. This implies a significant reduction in the volume of subsurface drainage. Indeed, Table 1 shows that in 1968 the east bank pipes were actually larger and more numerous than those on the west bank: the mean diameter of pipes on the east bank was 41% larger, the mean cross-sectional area of pipe outlets was almost twice as large, there were over twice the number of pipes, and the total area of these outlets and therefore also the density of piping in the bank were over four times greater than on the west bank. By 2003, this had completely changed. The mean diameter of east bank pipes was almost exactly the same as those on the west bank, the mean cross-sectional area was slightly lower than on the west bank, there were only four more pipe outlets on this bank than on the west, and the total area and density of piping was only 17% larger.

[30] The cross-sectional shapes of these east bank pipes also suggest that pipe erosion is less active than in 1968, with a very significant reduction in the number of lenticular outlets, especially horizontally lenticular ones. The overall reduction in vertical pipes on both banks also suggests that there is slightly less active downcutting in general than previously, although the changes on neither the individual banks nor the combined set are statistically significant.

[31] Perhaps the first issue that needs to be addressed is why the original 1968 survey found so much more pipe

activity on the east bank. There are a number of possible explanations that might act independently or in combination: (1) a larger catchment area on the east, (2) steeper slopes and hydraulic gradients on the east, (3) soils that are more susceptible to piping on the east, or (4) differences in bedrock properties, such as dip or permeability. Detailed analyses of soil properties in 1968, which focused specifically on properties relevant to piping erosion (aggregate stability, mean weight diameter of aggregates, pH, electrical conductivity, total cation concentration, texture, clay mineral species, organic matter and soil profiles), showed no differences between the two banks [*Jones*, 1971, 1981]. This is confirmed by the general soil classification map in the National Archive (CEH, 2006). The same uniformity applies to bedrock and surface drift deposits, as shown on the British Geological Survey 1:50,000 map sheet 100. There are, however, differences in distance to the divide and average slope. The distance from the east bank to the gritstone edge, which is the effective divide along this reach, is around 630 m, whereas the distance to the local divide on the west, the gritstone outcrop known as the Carl Wark, is only about 260 m. The eastern pipes therefore have around 2.4 times the catchment area, and in 1968 the east bank had almost exactly 2.4 times the number of pipes. In contrast, the mean slope on the western side is twice that on the east (14.8° against 7.2°), but it appears that catchment area is more important than slope in determining the severity of piping erosion here.

[32] One of the most notable changes over the 35 year period has been the reduction in the number of pipes on the east bank. Whereas in 1968 the east bank had more than double the number of pipes on the west bank, by 2003 there were only 21% more and the difference was not statistically significant. Both banks show some reduction in the clustering of pipe outlets, indicated by the nearest neighbor statistic, and an increase in the distances between pipes. However, the only trend that is statistically significant is the increase in the mean distance between pipes on the east bank. All the evidence therefore points toward a very significant reduction in pipe activity on the afforested bank, and only minor, statistically insignificant changes on the moorland bank.

[33] There could be a number of possible causes for these changes, especially the significant changes on the east bank: (1) reduced throughflow due to increased evapotranspiration resulting from afforestation, (2) artificial drainage of the hillslope diverting water away from the pipes on the forest bank, (3) decreased general climatic water balance reducing subsurface flows (affecting both banks), or (4) a major shift in the location of the channel, which would obliterate the original pattern of pipe outfalls and might destroy any interlinked pipes in pipe clusters, reducing pipe density. In this respect, it is possible that some of the smaller pipes in the original pipe clusters surveyed in 1968 were overflow pipes for the so-called "master" pipes; pipe flow monitoring by *Jones and Crane* [1984] demonstrated the existence of such overflow pipe systems in the Maesnant basin [*Jones*, 1997a, 1997b]. A similar effect could equally well be achieved by a reduction in pipe flow and erosion and subsequent infilling of the lesser pipes by soil creep processes.

[34] There is no evidence to support a general climatic source. There has been no significant change in rainfall: annual rainfall has remained fairly constant since 1961 (see section 2 and Figure 3). There is therefore no indication of a decline in rainfall that could explain any reduction in pipe dimensions and density. There is also no evidence of any change in evapotranspiration losses according to general climatological estimates (see section 2). However, MORECS only provides estimates for grid squares of 40 × 40 km. The system does use a realistic representation of local vegetation cover and runs a two-layer soil water balance model based on the average soil type for the grid cell. However, the area of afforestation on the east bank of Burbage Brook is only 33.5 ha, or about 1/5000th of the MORECS grid cell. Actual evapotranspiration in the Burbage plantation is likely to be somewhat higher than the MORECS estimate.

[35] There is strong evidence from elsewhere that afforestation causes a marked increase in local evapotranspirational losses. The long-term paired catchment experiment on the effects of coniferous afforestation undertaken by the Institute of Hydrology/Centre for Ecology and Hydrology (CEH) in the Plynlimon catchments in Wales has shown an average of 12% lower runoff from the forested catchment [*Blackie and Newson*, 1986], rising to over 15% in some years. CEH staff attribute this mainly to greater evapotranspirational losses from the forest due greater interception rates and higher radiant energy balances [e.g., *Hudson*, 1988; *Hudson and Gilman*, 1993]. Calder's detailed monitoring of energy and moisture balances above and beneath the forest canopy in the Hafren Forest at Plynlimon demonstrated that: (1) high rates of interception in the forest hold significant amounts of rainwater in the canopy where it is exposed to higher wind turbulence than on the ground, and (2) the lower albedo of the forest canopy captures more solar radiation than the moorland surfaces and this extra energy increases evaporation rates [*Calder*, 1985, 1986, 1990]. In modeling evapotranspiration from the forest, Calder concluded that total evaporative losses can best be estimated by assuming that all the surplus radiant energy is used in evaporation.

[36] Lateral erosion of the stream bank and channel migration might affect the spatial distribution of pipe outlets along the banks, if not their size. However, channel migration has been minimal. Figure 6 compares the channel pattern in the 1960s with the current pattern. The 1960s channel plan was derived from photogrammetric plotting based on air photography of 1962. The current course of the stream has been plotted from an aerial orthophoto from 2002. Although there has been more migration in this section of the stream than in the reaches upstream and downstream, it is still clearly insufficient to explain the gross changes in pipe location over the period (Figure 4).

[37] The other possible factor is artificial drainage. The Ordnance Survey 1:10,000 map of 1955 shows that a number of surface ditches existed on the eastern slopes of the clough section of the river prior to the 1968 survey. At the time of the original survey, one lateral drain approximately halfway up the valley sideslope would have intercepted drainage and directed it away from the study bank (Figure 1). Field observation in 2003 suggested that the percoline zone approximately 80 m upstream from the

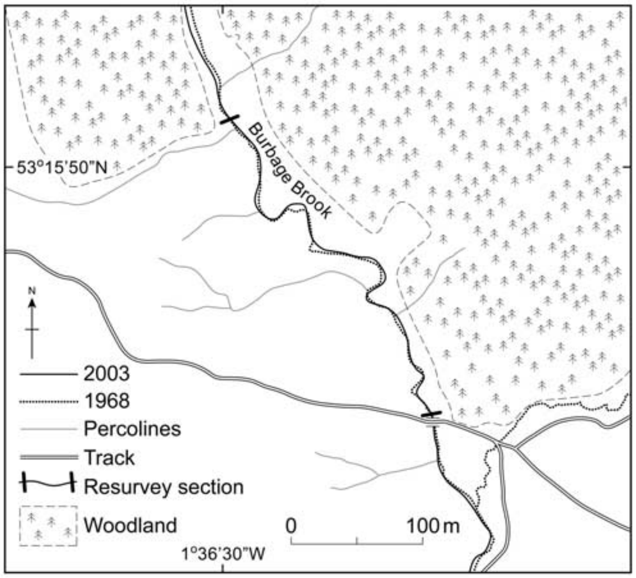

Figure 6. Channel changes along the afforested reach of the Burbage Brook between 1968 and 2003.

footbridge on the eastern bank (marked d on Figure 1) may have been ditched during afforestation, and close inspection of the 2002 orthophoto suggests there may be a few lateral ditches under the forest draining toward this ditch. However, the ditch system is long abandoned. The forest has never been managed commercially and it would appear that the ditching has never been cleared or renewed since the initial planting. There was no surface drainage water here at the time of the resurvey in the summer of 2003.

6. Conclusions

[38] The stream bank soil pipes of Burbage Brook have changed significantly over the 35 year period, but not in a consistent way: the pipes on the moorland bank have remained similar in size and number, but those on the bank afforested since the original survey are much reduced in both size and number. Evidence shows that changes in climatic water balance (precipitation and potential evapotranspiration) can be ruled out as a causative factor. It seems that the afforestation must have reduced the surface water balance by increasing interception and evapotranspiration. This has probably been supplemented by ditching at the time of planting, which would reduce the volume of throughflow feeding the east bank. However, the ditching is no longer very effective and has probably not been maintained for over 30 years.

[39] There is also no clear linear ancestry between the present-day pipes and those of the 1960s. The location of pipes and pipe clusters has changed markedly on both banks. Channel migration has been insufficient to be a major causative factor in these changes. The main explanation must be an inherent birth and death process, in which new pipes have developed and old ones have died off. Old pipes may have become blocked or more likely had their feeder catchment stolen by new cracks or other macropores and pipes diverting discharge further up pipe. New bank pipes may have been initiated as a result of this capture, perhaps also by Terzaghi's boiling process on the bank face, or else by desiccation cracking or mass movement cracking in the bank face; in other words, by hydraulic pressure and winnowing, or because of a new drainage route provided by other processes.

[40] These results do not contradict the hypotheses propounded by *Jones* [1971]. There is no further confirmation that soil pipes may develop into stream tributaries, over and above the evidence from partially collapsed roofs and bridged stream tributary channels already presented from Burbage Brook by *Jones* [1981, 1997a] and Maesnant in mid-Wales [*Jones*, 1997a]. The evidence presented here, however, is consistent with the view presented in 1971 that pipes may exist in quasi-equilibrium with the local water balance, and in this case study that balance has been altered by afforestation.

[41] The effects of afforestation indicated in this paper add a significant codicil to the links between piping and basin land use discussed in a recent paper on the management of upland basins in Britain [*Jones*, 2004]. Recent proposals for the expansion of woodland in England and Wales [e.g., *Tir Coed*, 2001; *Jones*, 2004] need to be considered in terms of the impact on the nature and pathways of hillslope drainage processes. The effects of afforestation on the overall water balance have been long established by experiments such as those of *Law* [1956] and the UK Institute of Hydrology/Centre for Ecology and Hydrology [e.g., *Hudson and Gilman*, 1993]. However, little is known about the effects on drainage pathways which the current paper clearly indicates. This is the first indication of the effects of afforestation on soil piping based on long-term sequential observations at the same site.

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