Soil Examination, Rainfall Simulation and Soil Runoff and Infiltration Experiments following a flood event in the Boscastle area

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Dr Nicholas Howden and Dr Lynda Deeks

National Soil Resources Institute

Cranfield University

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Executive Summary

The Environment Agency (EA) of England and Wales commissioned the National Soil Resources Institute (NSRI) of Cranfield University, to undertake field investigations near Boscastle, Cornwall, in order to investigate whether soil structure and land use practices could have caused an increase in surface water runoff during a recent high intensity rainfall event within the catchment. A large gulley was eroded as a result of runoff from grassland.

During July of 2007, a series of rainfall simulation experiments were undertaken, in pasture fields with different management histories, to compare surface water runoff rates under the same rainfall intensities.

Fields with similar soil but three contrasting soil structures and management histories were chosen: a permanent pasture field (>15 years) with very light grazing, with a good soil structure; a 7-year pasture field used to graze the herd, with a very poor soil structure; and a 4-year pasture field also used to graze the herd, with a relatively poor soil structure. Irrigation experiments were undertaken in each field, simulating a rainfall intensity of 36 mm hr^{-1}. For each the time to start of surface runoff and the accumulation of runoff volume with time was recorded. During the experiments, a number of other observations were made in respect of soil moisture conditions before and after irrigation, and the mechanisms of water flow through the soil. At each location, soil samples taken from a soil pit were analysed as part of a soil structural survey, bulk density samples were taken at a number of depths from the topsoil (0 to 22 cm) and infiltration tests were undertaken at each site using a double-ring infiltrometer.

The main experimental findings are as follows:

- there was a significant difference in surface runoff between the different land use intensities, both in terms of percentage runoff (from ~2% and ~60%), and in the steady-state flow of water from the irrigation plots (from 0.02 and 0.29 l min^{-1} m^2);
- steady state infiltration rates vary between 0 and 60 mm hr^{-1};
- the two fields with higher grazing intensity and younger pastures had more weakly developed soil structure, higher bulk density, increased runoff and lower steady state infiltration rates.

The implied effects of land management upon soil structure and therefore hydrological response to rainfall suggest that soil condition has a major influence on the capacity of the land to attenuate extreme rainfall events. If repeated elsewhere and widespread, then the degradation of soil structure could be a major contributing factor to the magnitude of flooding events.

Introduction

Following the flash flooding in August 2004 of Boscastle, north Cornwall, an extensive flood defence programme has been implemented within the catchment. However in June 2007 an intense rainstorm estimated at one stage to be of 30 mm h^{-1} intensity (EA source) again caused localised flash flooding. The recent flooding was less extensive due to the effectiveness of the new flood defence system. Flood damage was caused not by the river bursting its bank but by excessive surface runoff (eyewitness accounts). Surface runoff caused severe soil erosion in the top end of the catchment. The event raised questions relating to land use, infiltration capacity of the land and surface runoff generation. The aim of this brief project was to assess the relevance of land use management to surface runoff generation and to assess the need for and value of similar field research on a wider geographical area[n2].

Site Selection and Characterisation

The catchment area of the rivers Valency and Crackington that flow into Boscastle is dominated by grassland agriculture with woodland on the steep valley sides. The dominant soil series in the area is Denbigh, well drained fine loamy typical brown earths, which favour long-term grass because of their low vulnerability to surface poaching by stock. Three sites were selected to provide a range of land use histories. These were restricted to pasture areas, and were selected to provide a potential contrast between soil structure conditions of the same soil type (Denbigh). Fields were selected with the aim of representing soils with relatively poor (Site 1), moderate (Site 2) and good soil structure (Site 3).

Each site was characterised as follows:

- soil structure and bulk density survey;
- irrigation experiment:
    - initial characterisation of soil moisture around plot area and survey of plot characteristics (surface vegetation, slope etc.);
    - irrigation of marked plot at a rainfall intensity of 36 mm hr^{-1} (Figure 3);[n3]
    - measurement of time to start of runoff, and then collection of surface runoff volume at appropriate time intervals;
    - after cessation of irrigation, measurement of soil moisture conditions and note of time to cessation of runoff;
- infiltration experiments using double-ring infiltrometers.

Measurements of Runoff

Runoff Rate(s)

Figure 1 shows the response of each plot site over the period of irrigation. It is clear that the three soil structure types produce three different runoff rates, with the rate increasing from Site 3, to Site 2 to Site 1, from 0.02 to 0.29 l min^{-1} m^{-2}.

Percentage Runoff

Figure 2 shows the cumulative response of each plot, as compared with the cumulative volume of rainfall used during the period of irrigation. Once initial conditions are overcome, the gradient of these plots provides estimates of the percentage of incident rainfall that becomes instantaneous runoff. This suggests that the percentage runoff at the three plots varies from ~2% from site 3 to ~33% and ~60% for sites 2 and 1 respectively.

Observation of Flow Mechanisms

During the irrigation experiments, it was noted at sites 1 and 2 that a significant volume of water was flowing down gradient through the root zone in the shallow subsurface (0 to 3 cm) in addition to surface runoff. The volume of this observed “throughflow” could not be measured, but appeared comparable to the volumes of surface runoff collected. Given observation of this flow mechanism, it is not unreasonable to suggest that 90% of the incident rainfall was moving down gradient in the irrigation plot during the simulation period.

Measurements of Bulk density

Sample rings (5.4 cm diameter by 2 cm height) were used to collect three replica soil samples for bulk density analysis at 0-2 cm (surface), 5-7 cm, 10-12 cm and 20-22 cm, soil conditions permitting. Following collection, samples were stored in sealed plastic bags before being weighed and dried in a 105^{o}C oven for 24 hours. Dry bulk density was calculated from the sample oven-dry weights. Porosity was calculated using the dry bulk density and assuming a particle density of 2.65 g cm^{-3}.

The mean bulk density recorded for the Denbigh series, under permanent pasture, is 1.15 g cm^{-3} for the 0 to 22 cm horizon (Findlay et al., 1984). Figure 5 shows how bulk density values varied in the three soil profiles. Sites 1 and 2 had higher than average (1.15 g cm^{-3}) bulk density values, 1.16 g cm^{-3} and 1.28 g cm^{-3} (mean based on 0 – 22 cm profile), respectively. While Site 3 had a lower than average bulk density, 1.05 g cm^{-3} (mean based on 0 – 22 cm profile). Statistical comparison of the bulk density samples across the three sites showed only Sites 2 and 3 to be significantly different (95% confidence limit) in the surface soil (0 – 2cm depth). The rate of change in bulk density with depth (0 – 2 compared to 10 - 12 cm) was greatest at Site 1 where bulk density increased by 32 %. At Sites 2 and 3 bulk density increased by 22 % with increase in depth. These changes in bulk density with depth equated to an 18, 16 and 10 % (Sites 1, 2 and 3, respectively) reduction in porosity over the 12 cm depth.

Although a greater bulk density was recorded at Site 2 than Site 1 it is not possible to tell if this difference in bulk density relates to land management issues or simply the higher stone content observed in the samples collected from Site 2. However, in general, the two intensively grazed sites had an increased bulk density compared to the extensively grazed site. This implies that the extensively grazed site had a higher porosity than the intensively grazed sites. No specific zone of compaction can be identified from these results, however, bulk density and therefore compaction does increase with depth and this increase is greater under intensively grazed pasture and extensively grazed pasture.

Site and soil profile description

Site characteristic (Table 1) were noted before the start of the irrigation experiment. Site 3 was noticeably different from Sites 1 and 2, in that the grass density especially at ground level was denser, there was less evidence of animal trampling and damage to soil and grass sward, and the soil structure was visibly better at Site 3 than the other two sites. A 0.4 by 0.4 m soil profile was excavated less than 2 m from each of the rainfall simulation plots. Details of the profile descriptions are summarised in Table 2. Following the rainfall simulation experiment the down slope profile of the plot was excavated (Figure 4) and volumetric moisture content of the 0-5 cm and 5-10 cm layers were measured using a Theta probe. The 0-5 cm layer was notably wetter than the 5-10 cm layer (Table 3) particularly at Sites 1 and 2. At Site 3 volumetric water content results implied more water to be reaching greater depths in the soil profile.

Conclusions

These field experiments suggest that differences in topsoil structure are having a major influence on the rainfall-runoff and infiltration characteristics of land in one part of the Boscastle area which, by its soils, landscape and land use, is characteristic of much of the catchment as a whole. The sites investigated in this study imply that poorly developed topsoil structure is associated with runoff rates and percentages an order of magnitude greater than that from land with well developed topsoil structure.

It is reasonable to conclude that:

- topsoil structure is capable of strongly influencing the flow mechanisms that influence streamflow;
- present flood models that do not take account of soil structure could be providing grossly misleading flow predictions;
- if similar experiments elsewhere yield comparable results, there could be the opportunity to substantially reduce runoff volumes by the adoption of land management practices that protect and enhance soil structure;
- if soil conditions are such that they are promoting runoff and reducing infiltration, this has implications for recharge and the transport of solutes to the groundwater.

Acknowledgements

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Annex 1 Data tables and figures

Description		Site			
		Site 3	Site 2	-	Site 1
		permanent pasture	4-year pasture	7-year pasture 1	7-year pasture 2
Soil	Type	*Denbigh*	*Denbigh*	*Denbigh*	*Denbigh*
	structure	*Well developed*	*Poorly developed*	*Poorly developed*	*Poroly developed*
soil surface	Crumb	*plentiful*	*some*	*some*	*some*
	slacking	-	*some*	*some*	*some*
	Obvious pores	*yes*	*none*	*none*	*None*
	hoof marks (%)	-	*~5*	*~5*	*~5*
land use	time (years)	*>20*	*~4*	*~7*	*~7*
	stocking density	*7 to 12*	*80/40*	*80/40*	*80/40*
gradient (^{o})		*6*	*3*	*3*	*4*
vegetation cover[n6]	Canopy (%)	*100*	*95*	*95*	*95*
	Ground level (%)	*90*	*50~60*	*50~60*	*50~60*
	crop height (cm)	*13*	*8*	*10*	*10*

Table 1: Irrigation sites: physical, vegetation and soil characteristics. In respect of the 7-year pasture, only the data listed in column 2 are relevant to the discussion here.

Site	Site 1	Site 2	Site 3
Soil Description	Soil Association on 1:250,000 soil map: Denbigh. Well drained fine loamy and fine silty soils over rock. Elevation: 227. Slope 3^o, straight	Soil Association on 1:250,000 soil map: Denbigh. Well drained fine loamy and fine silty soils over rock. Elevation: 230. Slope 3^o, straight	Soil Association on 1:250,000 soil map: Denbigh: well drained fine loamy and fine silty soils over rock. Elevation: 166. Slope 6^o, straight
Surface	Canopy 95%, ground level cover 50-60 %, some hoof prints (< 1cm depth), average grass height 10 cm. Surface of soil: smooth, few granules, few/no macropores	Canopy 95%, ground level cover 50-60 %, some hoof prints (< 1cm depth) and wheel tracks could be seen in the soil, average grass height 8 cm. Surface of soil: smooth, few granules, few/no macropores	Canopy 100%, ground level cover 90-95 %, no poaching, average grass height 13 cm. Surface of soil: crumby, many very fine macropores[n7]
Colour	Dark brown. Occasional rusty coloured mottles observed around roots at 5 to 10 cm depth. Colour change from dark brown to yellowish brown at 35 cm depth	Dark brown. Soil too stoney to see any colour change in profile	Dark brown. No colour change seen down to 40 cm.
Structure	Few medium macropores, approx. 0.1% of area (worm borrows). Soil consolidated in situ but easily broke down to granular (2-4 mm) aggregates when removed from profile	Few medium macropores, approximately 0.5% of area (worm borrows). Soil consolidated in situ but easily broke down to granular (2-4 mm) aggregates when removed from profile	Fine macropores throughout profile. Approximately 5% pores in profile. Peds not visible in the in situ profile but soil easily breaks down into granular (2 – 4 mm) aggregates. Slightly more easy to break down than soil at Sites 1 and 2.
Compaction	0 to 1 cm depth knife inserted easily. Below 1 cm to bottom of profile knife hard to push in with little perceived difference with depth in profile	1 to 2 cm depth knife inserted easily. Below 2 cm to 10 cm knife hard to push in with little perceived difference with depth. Below 10 cm became easier to insert knife but not as easy as 1 to 2 cm depth.	firm resistance to penetration all the way down profile.
Stoneyness	Medium (2-6 cm) and large (6-20 cm), platy to subangular, approximately 5% stone content	Medium (2-4 cm) and large (12-9 cm), platy to subangular, more abundant than Site 1 and more noticeable at shallower depths (few 1-2 cm below surface)	Large (8 by 4 cm) stones throughout profile less abundant in 0 to 10 cm depth, becoming more abundant with depth especially below 20 cm. Shape: platy to subangular
Moisture	Soil moist. Refer to Theta probe measurements	Soil moist. Refer to Theta probe measurements	Soil moist. Refer to Theta probe measurements
Roots	Roots observed down to 40 cm, becoming less abundant quickly with depth. Main root accumulation at 0 to 3 cm depth. Roots fine/v.fine	Roots observed down to 40 cm. Main root accumulation at 0 to 2 cm depth, becoming less dense 2-8 cm and less dense again below 8 cm. Roots fine/v.fine	Roots fine, abundant down to 20 cm, becoming less abundant below 20 cm depth
Other	Many worms observed at 0 to 10 cm depth, few earthworm burrows extending down beyond 40 cm depth	Worms (more abundant than Site 1) observed at 2 to 5 cm depth, few earthworm burrows extending down beyond 20 cm depth	Earthworms present in profile but not as noticeable in the surface layer as at Sites 1 and 2. Wider variety of fauna in and around surface soil than at Sites 1 and 2. The soil felt springier under foot than Sites 1 and 2.

Table 2: Soil description

Depth in profile (cm)	Site 1	Site 2	Site 3
0 to 5	77 (41)	51 (40)	61 (46)
5 to 10	44 (38)	43 (37)	50 (37)

Table 3: Mean volumetric water content (m^3m^{-3}), down slope of rainfall simulator plot soil profile. Values in brackets represent mean volumetric water content in dry profile (recorded in profile pit).

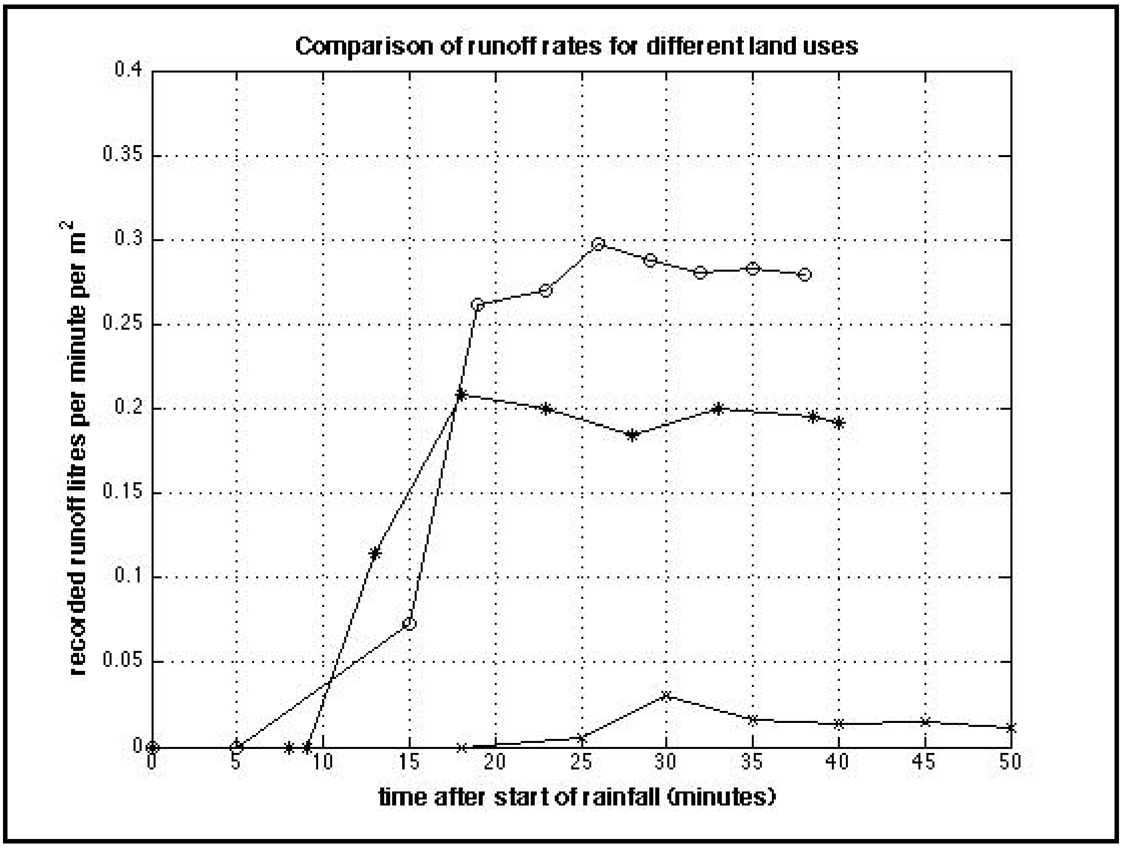

Figure 1: **Plots showing runoff rate (litres per minute per square metre) for site 1 (steady runoff rate ~0.275 $l.min^{-1}.m^{-2}$), site 2 (steady runoff rate ~0.19 $l.min^{-1}.m^{-2}$) and site 3 (steady runoff rate ~0.02 $l.min^{-1}.m^{-2}$), for an irrigation rate of 36mm per hour.**

Note: *Runoff rates have been adjusted to reflect small differences in rainfall rate during irrigation experiments and to express rates per unit area.*

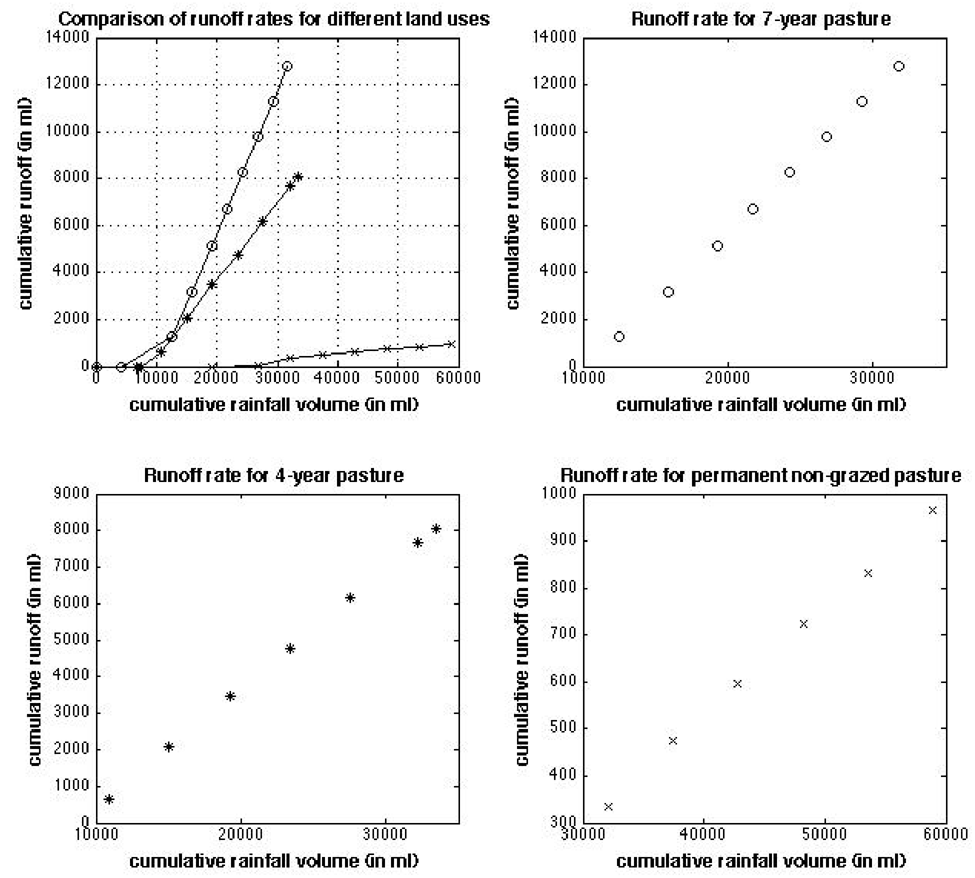

Figure 2: **Plots showing cumulative runoff volume compared to cumulative rainfall volume. The gradient of the lines represents the percentage of rainfall that becomes surface runoff once the ground is saturated i.e. for site 1 (7-year pasture, very poor soil structure), 60%, for site 2 (4-year pasture, poor soil structure), 33% and for site 3 (permanent lightly grazed pasture, very good soil structure), 2.3%.**

Figure 3: **Rainfall simulation in progress. Photograph shows irrigation plot (blue) with rainfall cups measuring rainfall volume, tray collecting down-gradient surface runoff (red) and collection of runoff waters (bottom left).**

Figure 4: **Photograph showing section of soil after irrigation. Notice that the top layer (~0 to 3 cm) is saturated, whilst the deeper soils remain dry.**

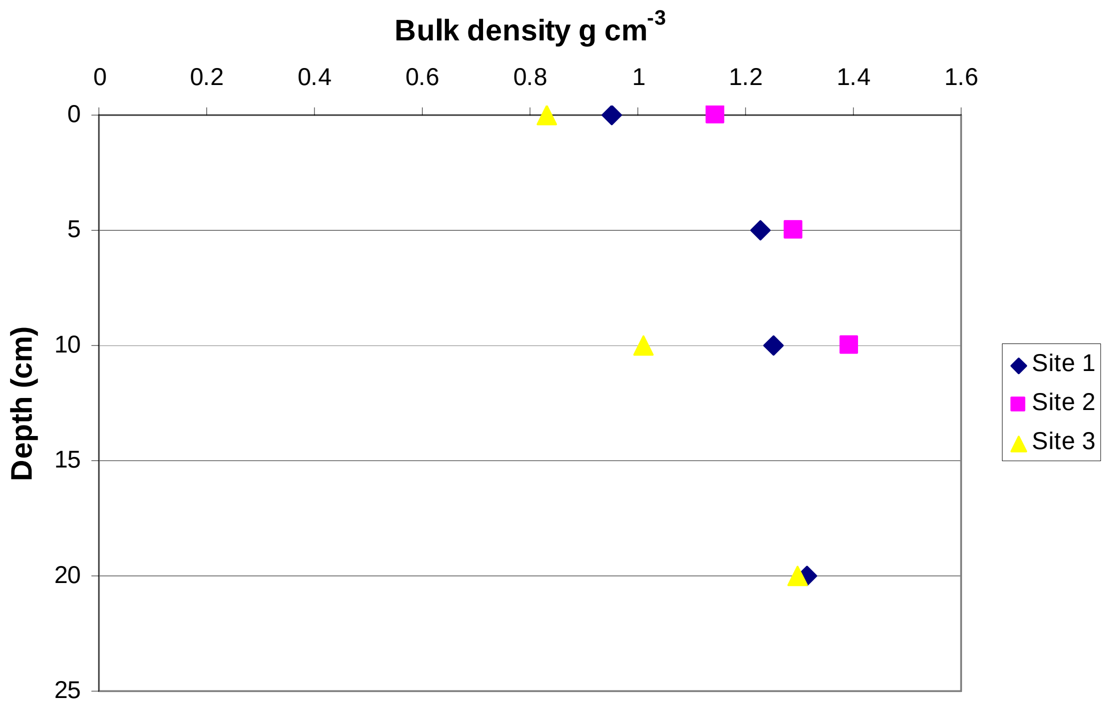

Figure 5 Variation of bulk density within the soil profile at the three Sites.

References

Findlay DC, Colborne GJN, Cope DW, Harrod TR, Hogan DV and Staines SJ (1984) Soils and their use in South West England. Soil Survey of England and Wales Bulleting No. 14, Harpenden