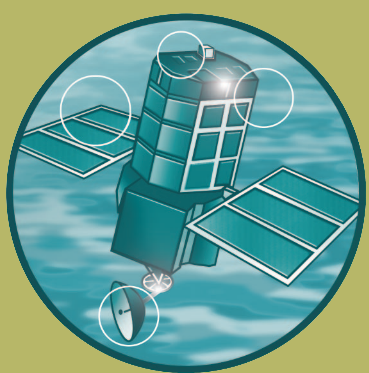
Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme

Review of impacts of rural land use and management on flood generation

Impact study report

Appendix C: Current state of managed rural land and mitigation measures

R&D Technical Report FD2114/TR



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R&D Technical Report FD2114/TR

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Statement of use
This report is aimed at those involved in land management. It provides the current position of knowledge and science with respect to land use management and its impact on flood generation. It will be of benefit to those seeking to reduce flood risk though specific land management practices, and those who wish to assess the impact of specific management practices on flood risk.

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Executive summary

FD2114/TR, the 'Impact Study Report', introduces the FD2114 project and gives a comprehensive review of the impacts of rural land use and management on flood generation. Project FD2114 is part of the Broad Scale Hydrology Modelling Programme (Calver and Wheater, 2001). This report, which constitutes Appendix C of FD2114/TR, the Impact Study Report, reviews the current state of managed rural land in England and Wales from the viewpoint of flood generation and mitigation.

The total areas under arable, grassland and rough grazing have remained reasonably constant over the last 50 years. However, livestock densities, crop types and management practices have changed significantly. The key changes in arable cultivation have been a shift from spring to winter-sown cereals and the introduction of new crops, most notably maize and oilseed rape. Livestock numbers have risen significantly over the last century and, more recently, the grazing season has lengthened. There has also been an increase in the area of woodland, mainly achieved by increased upland plantings.

In many cases, land use changes and the accompanying management practices have been linked to increased erosion and farm-scale runoff, and the degradation of soil structure. Of particular concern are winter practices that leave the soil surface bare or require the use of heavy machinery on the land, and also those actions that increase the surface and subsurface flow connectivity of the landscape, to give pathways for rapid runoff.

Several measures and practices have potential for mitigating flooding:

Soil surface protection: Practices that leave the soil surface bare or with little crop cover in the winter, especially if the soil has been worked down in to a fine tilth (for a seedbed), present the greatest risk. A vegetative cover on the soil, especially during periods of heavy and/or intense rainfall, helps to bind the soil particles together, increases surface roughness and absorbs the kinetic energy of incident rainfall. Transpiring crops remove water from the soil profile, thereby making it less susceptible to surface runoff generation.

Soil structural protection: Increasing the organic matter content of the soil improves its structure and infiltration properties. Avoidance of over-cultivation and over-compaction (leading to plough pans), together with the incorporation of crop residues, helps to encourage better infiltration into the soil surface in cropped areas. Lowering the stress on the soil, by reducing loads, decreasing tyre pressures and increasing tyre widths, can only be beneficial to the soil structure.

Flow connectivity: Ditches and culverts should be maintained, and in some areas it may be appropriate to install underdrainage. Cross-slope interceptors, such as grass buffers, ditches or hedges slow surface runoff and increase the likelihood of infiltration. Where possible, contour cultivations should be considered on land susceptible to surface runoff and erosion.

If not managed correctly, improved drainage provided by the open leg slot of mole drainage can cause peak runoff rates to be increased and the time to peak to be reduced. With correct management, however, the drainage can help provide buffer capacity to absorb rainfall and thereby reduce peak flows and the drained water can be released into lower sections of the catchment in a controlled manner.

Retention and storage: Increasing the roughness of the soil surface by mouldboard ploughing, or by creating small depressions, can provide several millimetres of temporary storage for surface runoff. A general return to smaller fields, with boundary hedges and ditches should be beneficial, and the banks or ridges often associated with hedges will help retard fast surface runoff. Retention structures such as small ponds and reservoirs also retard runoff, and can reduce the volume of runoff.

Contents

1. Introduction

The aim in this review is to develop an understanding of the current state of managed rural land in England and Wales from the viewpoint of flood generation and mitigation.

There are three main sections. Section 2 reviews the trends in agriculture over the last 100-150 years, in terms of land use, land management and crop and livestock husbandry. This section includes a substantial amount of data. Section 3 considers the current state of farming and reviews the impacts of farming on flood generation. Section 4 reviews measures and practices that can be used in flood mitigation.

2. Trends over the last 100-150 years

This review of trends in agriculture over the last 100-150 years is based on Government farm statistics, published literature and personal communications. The following land use groups were considered, in terms, where appropriate, of land use, land management and crop and livestock husbandry:

- Cereals, oilseed rape and maize
- Fodder crops
- Root crops
- Other allied management systems
- Grassland
- Livestock
- Woodland and forests

2.1. Key changes to UK agriculture

A number of key changes are evident from the data and are summarised below:

- The 1947 Agriculture Act - sought to attain self-sufficiency in food production in the UK led to initial intensification;
- Entry into the European Community in 1973 which resulted in expansion of crop types and a rapid rise in area of some specific crops - e.g. the rise in Oilseed rape from 92,000ha (1.8% of cropped area) to 500,000ha (10.2%) in 1998;
- The general progressive change from spring-sown to autumn sown cereals;
- Changes in trafficking, including an increase in the use of on-farm contract machinery and working at unfavourable times to the soil status, e.g. later (mid-winter) sugarbeet harvesting;
- An increase in grazing animals; cattle numbers have increased three fold in England & Wales since 1866 although were broadly steady or falling from 1980. At the same time, sheep numbers rose sharply from 1980 onwards;
- The change from hay to silage and the use of intensive grassland, and more recently the move towards longer grazing seasons;
- A general reduction in drainage status following cessation of grant aid;
- A gradual reduction in new plantings of coniferous forests with an emphasis towards deciduous farm woodlands, especially in the South East.

The summary picture of land use in UK agriculture is given for the period 1929 to 1987 in Table 2.1, and general land use changes are illustrated in Figures 2.1, 2.2, 2.3 and 2.4, which are based on Government census data.

	1929	1938	1942	1950	1955	1960	1965	1970	1975	1980	1981	1982	1983	1984	1985	1986	1987
Total area of UK	724400	24400	24400	24400	24400	24400	24410	24410	24105	24088	24089	24088	24088	24088	24085	24085	24085
Area of agricultural land							19621	19124	18978	18953	18808	18783	18735	18720	18703	18676	18652
% agricultural land							80.4	78.3	78.7	78.7	78.7	78.0	77.8	77.7	77.7	77.5	77.4
Crops & grass total	13172	12851	12626	12597	12587	12489	12408	12143	12028	12136	12085	12083	12078	12095	12080	12088	12116
Arable	5783	5244	7081	7428	7099	7035	7496	7199	6954	6996	6982	6986	6970	6990	7061	7010	7008
Grass over 5 years	7389	7607	5547	5167	5476	5184	4912	4944	5074	5140	5103	5097	5107	5105	5019	5077	5108
Rough grazing including common			8583	6921	6929	7406	7216	6692	6555	6333	6235	6198	6139	6107	6088	6045	5989
Woodland on farms								153	225	271	277	286	292	296	312	316	547
All other land								135	170	213	211	217	226	219	223	227	

Table 2.1 Land area used by agriculture (000 ha)

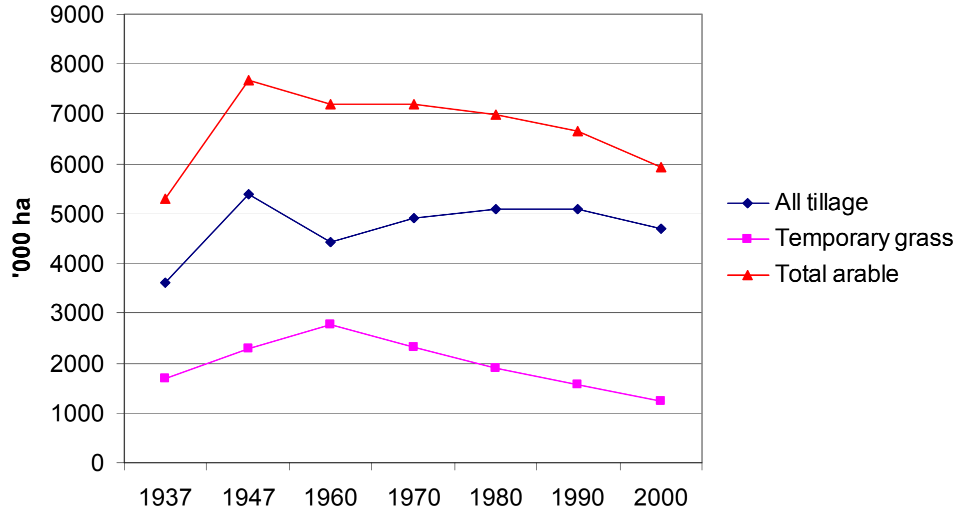

Figure 2.1 UK arable area

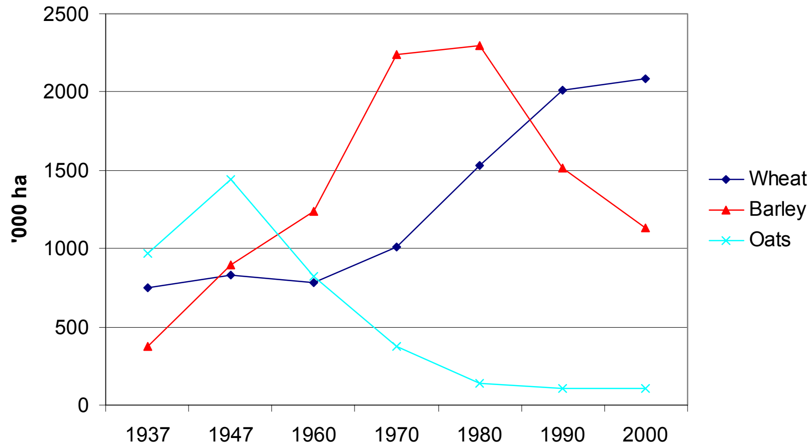

Figure 2.2 UK cereal area

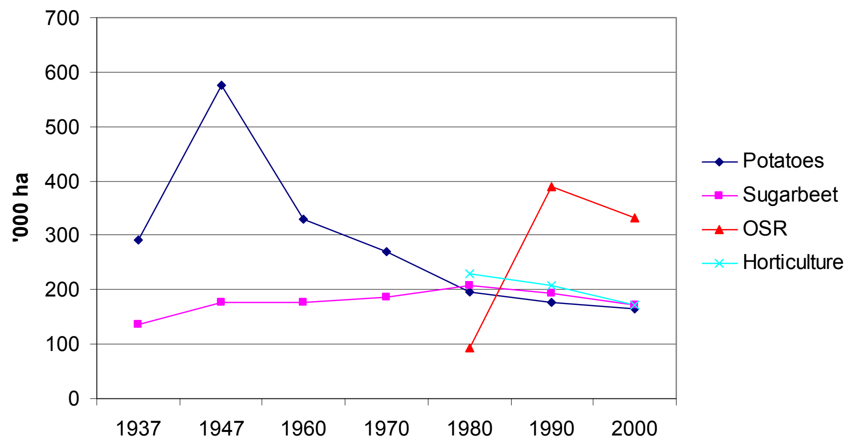

Figure 2.3 UK 'other crops' area

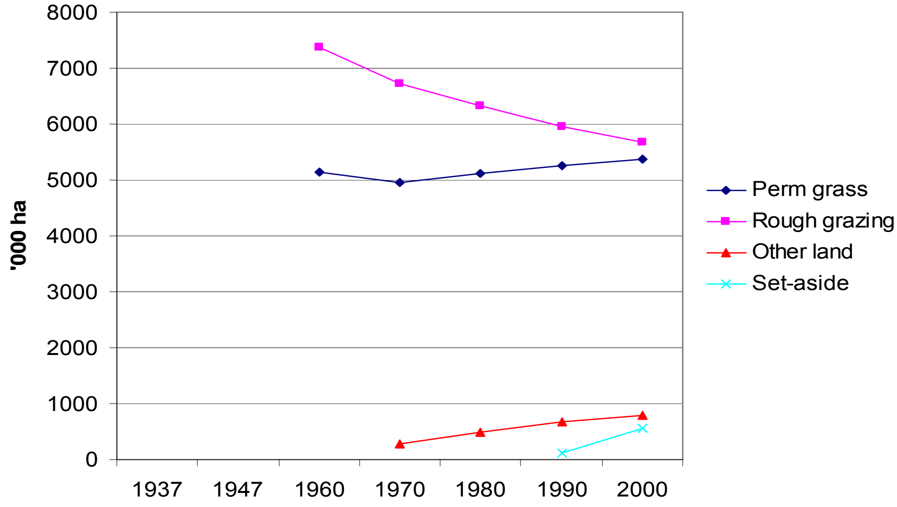

Figure 2.4 UK areas of grass, other land use (inc. woodland) and set-aside

2.2. Key agricultural statistics

The agricultural systems considered are listed in Table 2.2. This includes a number of farm systems where no impact on runoff was expected, and which therefore may offer alternative use of the land where there is a clear risk of flood generation from a companion system (e.g. relatively benign indoor pig production versus outdoor production where runoff and erosion problems have been demonstrated).

Cereals, oilseed rape and maize

Summary data in Tables 2.3 and 2.4 and Figure 2.2 (cereals) and Figure 2.3 (OSR) provide background information on the cropped areas. The increase in cereal production observed was largely due to increase in yields; during the past 20 years there has been little change in the area sown to cereals, with the total ranging from 3.8 to 4 m ha (see Figure 2.2). The area sown to oats has fallen continuously over last 50 years. Virtually all winter wheat is grown in England (94% in 1986) but barley production is more widespread. In 1986, of the barley grown, 75% of the total was in England, 21% in Scotland and 2% each in Wales and Northern Ireland.

Livestock[a]	Beef production	Organic extensive
		Intensive (12 month) beef
		Extensive suckler beef (calves to weaning)
		Indoor grass silage beef and indoor finishing of suckled calves
		Dairybred beef finished at 18/24 months
	Poultry/egg production	Organic broilers
		Intensive broilers and turkey
		Free range broilers and turkey
		Ducks
	Sheep	Extensive hill sheep
		Organic lowland sheep
		Conventional lowland early/spring lambing
	Dairy (milk)	Organic (mixed grass and forage)
		All grass farm (western UK)
		Storage feeding (mixed farm in eastern UK)
	Pigs	Organic outdoor
		Outdoor breeder
		Indoor finisher and breeder
Cereal cropping[b]	Organic	
	Intensive arable	
	Integrated Crop Management	
Non-cereal cropping	Oilseed rape	Organic
		Intensive arable conventional OSR
		Intensive industrial OSR
		Intensive arable (min. cultivation)
	Potatoes	Organic
		Intensive (Irrigated)
		Intensive (Unirrigated)
		Early/second early potatoes
	Horticultural crops (e.g. tomatoes)	Organic
		Conventional soil grown, early planted
		Conventional soil grown, late planted
	Sugarbeet	
Non-arable land[c]	Permanent grass	
	Rough grazing (including moorland)	
	Forestry	
	Other land	
	Set-aside	

Table 2.2 Agricultural systems

Notes:

a Consider impact of stocking rates and grazing season.

b Differentiate between wheat, rye, barley, oats, maize, mixed corn - where relevant. Consider cultivations - mouldboard ploughing /minimal plus direction. Consider autumn/spring cropping issues.

c Consider underdrainage and land drainage, cultivations, tramlines, and landscape features.

Crop	1937	1947	1960	1970	1980	1990	2000
Wheat	751	834	781	1010	1532	2014	2086
Barley	376	895	1238	2243	2293	1518	1128
OSR	n/a	n/a	n/a	n/a	93	390	332

Table 2.3 Total crop area in UK ('000ha)

Cereals/oilseed rape. In the last 20-30 years there has been a significant shift in UK arable production towards the growing of winter cereals, especially winter wheat (see Table 2-3). Winter wheat is now generally all drilled in September, whereas 20 years ago it was not drilled until October. The widespread production of oilseed rape (OSR) in the UK did not take off until the 1980s. Oilseed rape began as a crop in the UK in 1970s, initially as a break crop in cereals, but there was a sharp increase from the mid 1970s, followed by a remarkable rise to 390,000 ha in 1987. OSR is generally drilled in the period from late August to early September. Based on seed sales data, the percentage spring vs. winter Oilseed rape area has reduced from 34% in 1995/96 to 17% in 2001/2002. Earlier drilling means that the prepared seedbed is drilled and rolled down earlier in the autumn. Seedbeds with less fine tilth are now more common (better drills available), but the degree of heavy pressing after drilling of the seed to improve seed-soil contact has significantly increased (A. Wells, *Pers comm.)*. Severe compaction now occurs on headland areas where the heavy press/roll is turned.

In respect of different arable crops and cultivation practices – there is some difference in drilling dates between winter wheat, winter barley and oilseed rape (P. Blundell, *Pers. comm.*), but whether this is sufficient to cause different runoff patterns is not known. Table 2-5 shows regional differences in area and yield of winter wheat and barley.

Maize. The introduction of maize (especially forage maize) production in the UK has taken place over the last 15 years. In England, about 33,000 ha of maize was grown in 1990, rising to just under 120,000 ha by 2001. Maize is drilled in April/May and harvested in mid-Sept/mid-Oct. In more recent years the rate of increase has slowed significantly (A. Wells, *Pers comm.*). Forage maize is often grown continuously on the same land. Harvesting by heavy machinery in September/October can damage soil structure. Most forage maize is now harvested by contractors who do not take account of the weather or soil surface conditions when deciding whether to harvest or not. Growers and/or their contractors leave harvesting the crop until late autumn. Maize fields are usually left over winter prior to the pre-drilling cultivations in the following spring. The situation is aggravated by the fact that drilling and harvesting is nearly always carried out up and down the slope. The reason for this is that the harvesting machinery is very heavy and if used across the slope its slides sideways.

The practice whereby farmers often take the opportunity to spread slurry or solids from livestock to maize over the winter period means more untimely trafficking of the soil and consequent soil structural damage. The less than ideal conditions leave large ruts that quickly become preferential drainage channels. The lack of vegetation cover in maize fields during the summer months make the soils susceptible to erosion from summer thunderstorms (Boardman, 1996).

	Wheat[a]			Barley[c]			Oats[b]		
	Area	%W	%S	Area	%W	%S	Area	%W	%S
1970	1,010	86	14	2,243	7	93	375	21	79
1971	1,097	91	9	2,288	8	92	362	27	73
1972	1,127	92	8	2,288	9	91	315	32	68
1973	1,146	92	8	2,267	10	90	281	32	68
1974	1,233	92	8	2,214	10	90	253	29	71
1975	1,035	88	12	2,345	10	90	232	29	71
1976	1,231	96	4	2,182	14	86	235	43	57
1977	1,076	94	6	2,400	14	86	195	40	60
1978	1,257	95	5	2,348	18	82	180	39	61
1979	1,371	96	4	2,343	25	75	136	40	60
1980	1,441	97	3	2,330	31	69	148	34	66
1981	1,491	97	3	2,329	36	64	144	46	54
1982	1,664	97	3	2,221	41	59	130	48	52
1983	1,695	8	2	2,143	43	57	108	50	50
1984	1,939	99	1	1,978	53	47	106	50	50
1985	1,902	98	2	1,966	52	48	134	52	48
1986	1,997	99	1	1,916	50	50	97	60	40
1987	1,994	97	3	1,831	53	47	99	43	57
1988	1,886	94	6	1,879	46	54	120	37	63
1989	2,083	93	7	1,653	53	47	119	50	50
1990	2,042	96	4	1,522	58	42	106	51	49
1991	1,981	97	3	1,393	62	38	103	59	41
1992	2,067	97	3	1,297	61	39	100	58	42
1993	1,759	95	5	1,166	56	44	92	54	46
1994	1,811	95	5	1,108	57	43	109	60	40
1995	1,859	98	2	1,193	58	42	112	68	32
1996	1,976	98	2	1,269	59	41	96	71	29
1997	2,036	98	2	1,359	62	38	100	74	26
1998	2,045	98	2	1,253	61	39	98	75	25
1999	1,847	97	3	1,179	46	54	92	67	33
2000	2,086	96	4	1,128	52	48	109	72	28
2001	1,635	97	3	1,245	46	54	112	68	32

Table 2.4 UK Estimated areas of spring (S) and winter (W) cereals ('000 ha)

Notes:

a 1970 to 1978 - proportions of winter and spring varieties recorded in the Seed Sales Survey.

b 1979 to 2001 - proportions of winter and spring varieties recorded in the Seed Certifications Scheme.

c For barley from 1985 - proportions of winter and spring varieties recorded in the June Census results. 2000 - proportions of winter and spring varieties recorded in the Seed Certifications Scheme.

Defra's latest farm practices survey confirms that substantial amounts of cattle farmyard manure (FYM) and slurry are disposed of within the farm by spreading to cereal crops. For FYM, 29 tonnes/ha is applied to spring-sown crops and 19 tonnes/ha to grassland, on average - although there is a wide range in practice. For slurry, the average application is 47 m^3/ha applied to spring-sown crops and 35 m^3/ha to autumn sown crops. The most common primary cultivation to incorporate the FYM/slurry is the plough, although on heavier land there tends to be a greater use of a heavy disc.

Fodder crops

These include forage legumes, turnips/swedes and whole crop cereals.

Forage legumes (e.g. lucerne, lupin, and sainfoin). Little relevant data or literature was found. Most of the information available related to nitrate leaching. Turnips, swedes and mangolds used to be fed to cattle and, to a lesser extent, sheep during the winter and early spring. This is now much less common, with the fall off in root crops completed by 1980s. There was a marked disappearance of these crops due to high labour costs and low profitability compared to other arable crops.

Root production for feeding stock began to decline in 1930. After the Second World War the area fell further - turnips/swedes now represent only about 10% of the 1860 level and 33% of the 1930 level.

Whole crop cereals. The area is increasing, as the crop is an alternative to maize, and probably more environmentally friendly generally, and probably particularly to surface runoff. Grazing white clover as an understorey probably also reduces runoff further as well as bestowing other benefits.

Root crops

Potatoes. Early crops, which are lifted by 31 July, represent 5% of the total production in the UK. Prior to World War II, the area planted was fairly constant at 300,000 ha. After 1939, this increased rapidly but since the 1950s a slow but continuing decline has occurred; see Figure 2.3. There has been a considerable increase in the average area per producer. Information from Weatherhead & Danert (2002) showed that in 1995 there were about 62,000 ha of irrigated potatoes (early and maincrop) in England. This compares to Defra statistics that show for all potatoes (irrigated and unirrigated) there was 130,000 ha grown in England. Of these, irrigated potatoes were 48% of the total.

In 2001 there were about 77,000 ha of irrigated potatoes. From Defra statistics there were 126,000 ha of potatoes (in total) with 61% of the total irrigated.

Until the major drought in 1976, hardly any potatoes were irrigated at all. The availability of irrigation post 1976, means that more potatoes are now grown on much lighter soils (which are prone to surface runoff and erosion). Stone separation has also allowed more potato production on land more prone to erosion. It is evident that irrigation of potatoes on sloping land is common and can create runoff/erosion problems. Generally a (late planted) winter cereal or a spring cereal is grown after potatoes.

WHEAT	AREA								YIELD								PRODUCTION							
	95/96	96/97	97/98	98/99	99/00	00/01	01/02	02/03	95/96	96/97	97/98	98/99	99/00	00/01	01/02	02/03	95/96	96/97	97/98	98/99	99/00	00/01	01/02	02/03
North East	70	77	78	76	64	76	54	71	8.41	8.65	7.17	6.50	7.40	7.70	6.80	8.10	590	670	560	500	470	590	370	570
North West	236	254	28	29	23	28	17	29	8.11	8.50	6.78	6.20	6.70	7.10	5.10	6.80	1,920	2,160	190	180	160	200	90	184
Yorks and Humbs	363	385	259	255	234	258	199	247	7.93	8.25	7.29	7.70	8.20	8.30	7.60	8.50	2,880	3,170	1,890	1,960	1,920	2,140	1,510	2,105
East Midlands	319	336	395	393	362	401	319	386	7.89	7.86	7.16	7.80	8.40	8.20	7.00	8.30	2,520	2,640	2,830	3,080	3,040	3290	2,220	3,195
West Midlands	410	433	165	165	150	167	127	165	7.32	8.03	7.39	7.10	7.60	7.50	6.40	7.50	3,000	3,470	1,220	1,170	1,140	1,260	810	1,225
Eastern	167	183	521	525	490	545	452	520	7.16	7.94	7.74	8.20	8.40	8.20	7.30	7.90	1,200	1,450	4,030	4,300	4,140	4,460	3,310	4,354
South East	143	156	264	265	243	278	207	261	7.03	8.31	7.38	7.30	7.90	7.80	6.90	7.90	1,000	1,300	1,940	1,940	1,910	2,160	1,420	2,076
South West	23	25	197	199	181	204	166	191	7.28	7.59	7.09	6.70	7.40	7.40	6.80	7.50	160	190	1,390	1,320	1,330	1,500	1,140	1,446
England	1,732	1,852	1,905	1,911	1,746	1,957	1,541	1,869	7.67	8.14	7.37	7.60	8.10	8.00	7.10	8.00	13,280	15,080	14,050	14,500	14,110	15,590	10,860	15,155
Wales	11	13	15	16	13	15	11	16	7.51	7.87	6.78	6.40	6.10	7.40	6.30	7.60	90	100	100	100	80	110	70	112
England & Wales	1744	1,866	1,920	1,927	1,759	1,972	1,552	1,885	7.66	7.99	7.37	7.60	8.10	8.00	7.04	8.10	13,366	14,900	14,150	14,600	14,190	15,700	10,930	15,267
Scotland	108	104	109	111	84	109	80	97	8.25	8.32	7.56	7.40	7.80	8.80	7.70	7.50	894	865	820	820	660	960	620	739
Northern Ireland	7	7	7	7	3	5	4	7	7.78	7.54	7.02	6.90	6.80	7.30	6.20	6.20	51	52	50	50	20	40	30	47
United Kingdom	1,859	1,976	2,036	2,045	1,846	2,086	1,635	1,989	7.70	8.15	7.38	7.60	8.00	8.00	7.10	8.00	14,310	16,100	15,020	15,470	14,870	16,700	11,570	16,053

BARLEY	AREA								YIELD								PRODUCTION							
	95/96	96/97	97/98	98/99	99/00	00/01	01/02	02/03	95/96	96/97	97/98	98/99	99/00	00/01	01/02	02/03	95/96	96/97	97/98	98/99	99/00	00/01	01/02	02/03
North East	61	63	49	46	44	43	50	41	6.25	7.02	6.26	5.20	5.60	6.10	4.90	6.20	380	440	310	240	240	260	250	256
North West	127	129	47	43	44	39	46	40	6.18	7.05	5.81	4.50	4.80	5.60	4.60	4.90	780	910	270	190	210	220	210	197
Yorks and Humbs	110	114	139	130	122	122	145	110	5.78	6.50	6.36	5.80	6.10	6.20	5.80	6.40	640	740	880	760	750	750	850	709
East Midlands	143	152	127	115	98	100	105	87	5.92	5.48	5.90	5.60	6.10	6.00	5.50	6.00	850	840	750	650	590	600	570	524
West Midlands	154	165	92	84	74	72	74	62	5.72	6.10	6.46	5.60	5.20	5.50	4.70	6.10	880	1,010	590	470	390	390	350	380
Eastern	134	141	219	195	174	169	193	158	5.44	5.80	6.10	5.90	5.80	6.20	5.40	5.80	730	820	1,330	1,160	1,010	1050	1,040	925
South East	82	85	124	107	94	89	101	78	5.72	6.62	5.80	5.50	5.80	5.80	5.20	5.80	470	560	720	590	550	510	520	451
South West	26	25	148	135	124	118	134	111	5.14	6.04	5.41	4.90	5.40	5.40	5.20	5.40	130	150	800	660	670	640	700	599
England	837	877	944	856	774	752	848	689	5.80	6.25	5.99	5.50	5.70	5.90	5.30	5.90	4,860	5,480	5,660	4,720	4,410	4,430	4,490	4,041
Wales	32	32	34	30	30	26	27	24	4.71	5.73	5.19	4.60	5.20	4.60	4.70	5.00	150	180	170	140	150	120	130	121
England & Wales	869	909	978	886	804	778	875	713	5.77	6.16	5.99	5.50	5.70	5.90	5.28	5.84	5,010	5,600	5,830	4,860	4,560	4,550	4,620	4,162
Scotland	290	324	344	334	339	316	337	325	5.72	5.97	5.27	4.90	5.40	5.60	5.70	5.20	1,658	1,936	1,810	1,620	1,840	1,770	1,920	1,700
Northern Ireland	34	34	36	35	36	33	33	28	5.16	5.27	4.88	4.40	4.70	5.50	5.10	4.10	173	181	180	150	170	180	170	114
United Kingdom	1,192	1,267	1,358	1,255	1,179	1,127	1,245	1,066	5.73	6.14	5.76	5.29	5.58	5.80	5.40	5.60	6,830	7,780	7,820	6,630	6,580	6,490	6,700	5,975

Table 2.5 UK area, yield and production by region.

Notes:
1996/97 data is presented using Standard Statistical Regions, 1997/98,1998/99 and 1999/00 data is presented by Government Office Region, consistent with the policy.
02/03 - provisional data

Sugarbeet. This represents about 7% of the crop output. Sugarbeet was introduced in 1920s and was regarded as a useful break crop and cash crop. There were increases in area of sugarbeet until 1980. There are now few holdings and the number has fallen by 50% during the 20 years to 1987 when the area was just 11,000 ha. Sugarbeet is now between 5-15% of total crop as irrigated (2002).

Sugarbeet harvest dates - due to current number and location of British Sugarbeet processing factories (e.g. Newark) the harvesting of sugarbeet may take place at any time between late September and the following February (P. Blundell, *Pers comm.*). This means field/soil trafficking can occur over the winter period, with possible soil damage. Until about 5 years ago (1995+) harvesting was generally completed by late December, but closure of some sugarbeet factories has meant that the harvesting period has been extended. Heavy machinery (often contract harvesters) is used. There has also been a move towards bigger harvesters that can lift six rows of beet at once, rather than the older single row machines. Harvesting is therefore undertaken faster (once it is started) than it used to be.

Carrots. Almost all carrots grown in the UK are now irrigated. Carrots may be harvested (due to supermarket demands) in the January to March period. Harvesting of both carrots and sugarbeet in winter may create soil compaction and puddling that may help generate runoff. Spring Oilseed rape may be grown after sugarbeet or carrots.

The de-stoning of soils to grow large areas of root crops (with extensive ridge and furrow systems) in areas where they were not previously grown may also have altered the dominant water flow routes through these soils, especially where substantial amounts of irrigation water are applied.

Other allied management systems

Set-aside. The area in the UK under set-aside has risen from 110,000 ha in 1990 to 567,000 ha in 2000; see Figure 2.4. Many farmers now use set-aside as a formal part of their crop rotation. This means that the set–aside fields on a farm are not necessarily the same ones each year. Set-aside is being used as a break crop. Also, some set-aside land is being drilled with non-food OSR, so the soil is cultivated rather than being left uncropped. Set-aside can provide a buffered area alongside a stream or river, but in the UK this is rarely designed as a means to reduce surface runoff to the watercourse.

Herbicide treatment. An interesting recent development has been the increasingly widespread use of the herbicide glyphosate on arable land. This herbicide is now very cheap and farmers use it to produce sterile stubble prior to the subsequent cultivations to control persistent weeds or just prior to a field going into set-aside. The consequence of this is that the field surface is devoid of growing vegetation and incident rainfall is not effectively intercepted.

Grassland

There are many references relating to nutrient losses, (especially nitrate and phosphorus), particulates and soil erosion from grassland and other forage crops. Although a large number of the references discuss the nutrient or pollutant loading present in runoff water, e.g. Haygarth & Jarvis (2002), Scholefield *et al.,* (1993), few contain information relating to the volume of runoff emanating from these crops. The general thrust of most of the work reported in the literature, therefore, most often relates to the concentration of the pollutant(s) in the runoff rather than containing information about the frequency, level and factors affecting runoff volumes or the likely contribution made to flood risk.

The emerging consensus view is that changes in grassland husbandry techniques, especially in the last 20 years has led to greatly increased levels of surface runoff. Increasing stocking rates has led to a trampling effect, where the soil surface is sealed and infiltration greatly reduced, leading to much increased runoff. The problem is compounded by the fact that many of our grass growing regions are in areas of high rainfall. Total area to grass is illustrated in Figure 2.4. There is considerable economic pressure on livestock farmers to extend the grazing season and to utilise grass by grazing more than at present - grazed grass is vastly cheaper as a feed than the use of concentrates and less costly than conserved herbage in the form of silage or hay. Headage payments have encouraged high stocking rates, but the replacement of these by area payments may help the situation.

Modelling work indicates that rainfall on grassland areas is more likely to generate runoff under heavy grazing. Additionally measurements e.g. by Heathwaite *et al*. (1989), found that during their measurement period surface runoff from heavily grazed permanent pasture in Devon was 53% of total rainfall compared to 7% from ungrazed land. Poaching or severe trampling of grassland around feeding troughs and in gateways are point sources of surface runoff.

Livestock

Cattle. Cattle numbers peaked in the 1980s then fell back in the 1990s. In 1922, 75% of UK cattle were in England & Wales, 15% in Scotland and 10% in N. Ireland. Little change took place in the 1930s and World War II. Cattle have become relatively less important in England & Wales since the mid 1950s (as land was more suitable for profitable crop production) while in Scotland and Northern Ireland the opposite has occurred. Extended grazing seasons, and the cost of feed have increased the pressure on the land with a greater consequent risk of ground compaction (trampling and poaching).

Sheep. There was a sharp rise in the 1980s in sheep and lamb numbers. Typically there were 25-30 m during the 1930s and World War II but this then fell to 17m in 1947. From 1956, profitability began to improve and the numbers rose to 30 m. Following CAP for sheep meat, numbers rose further in the 1980s to just under 40 m. The increases in recent years have been largely due to a relative decline in profitability of suckler calf production in uplands and milk and beef production in other regions, resulting in a switch to sheep meat production. There is anecdotal evidence and some data to suggest that the increase in sheep numbers has led to compaction in the uplands (see later).

Pigs. Pig production was about 4.5 m head in 1935 but declined to *c*. 2 m during WWII. Rise in pig numbers was, however, evident thereafter, peaking at close to 9 m in the mid 70s and staying at *c.* 8 m through the 80s and 90s. Changes in the pig market at the end of the 90s meant that the population has declined to 5 m in 2003. Information on effects is limited as the literature mostly relates to quality of runoff and pollution by nutrients.

Outdoor pig production has expanded rapidly in recent years and the trend may continue following the ban on sow stalls (a method of indoor production) which came into force in 1999. Little was known of the incidence and nature of pollution from land stocked with outdoor pigs of the potential polluting effects of runoff from such land.

A survey of outdoor pig units was undertaken with the assistance of companies servicing the pig industry in 1997 (EA, 1997). The location of each sample herd was related to soil-type, proximity to watercourses and other water features, land drainage, slope, erosion risk and rainfall and the following characteristics identified: stocking rate and type, tenure, previous crop, and vegetation at the time of survey. Risk scores were estimated for six factors and these were accumulated to provide an overall assessment of pollution risk from the sample sites.

The main risk factors identified for any outdoor pig site are its proximity to surface waters and/or the presence of an underlying aquifer. Pollution risk can be reduced by identifying and controlling vectors that might be used by water moving overland and by sensitive location and layout of units to reduce the potential for generation of surface runoff.

Poultry. There has been a dramatic rise since 1960 and numbers are continuing to rise. Poultry meat supplies increased from 100,000 tonnes to 1,000,000 tonnes from 1955 to 1987. No significant adverse effects are seen from poultry, other than more direct runoff from poultry housings.

Woodland and forests

Table 2-6 summarises data on the area of woodland in the UK (and by country) since 1924, split into coniferous and broad-leaved plantings. The forestry area has greater than doubled over the last 80 years. The increase in forestry plantings in the period 1980–90 was due to private supply exceeding Forestry Commission new plantings every year. Total forestry and farm woodlands increased to 2,400,000 ha 1990, but agricultural holdings represented only 2% of the area in 1982. Forestry and woodland represents about 11% of the UK land area.

Total						
	England	Scotland	Wales	GB	N Ireland	UK
1924	660	435	103	1,198	13	1,211
1947	755	513	128	1,396	23	1,419
1965	886	656	201	1,743	42	1,785
1980	948	920	241	2,109	66	2,175
1995-99	1,097	1,281	287	2,665	81	2,746
2001	1,100	1,317	289	2,706	83	2,789
2002	1,104	1,324	288	2,716	84	2,800

Conifers						
	England	Scotland	Wales	GB	N Ireland	UK
1924	170	378	46	593	11	604
1947	234	406	67	707	19	725
1965	461	603	168	1,233	34	1267
1980	429	837	177	1,443	55	1,498
1995-99	372	1,045	163	1,580	65	1,645
2001	372	1,053	168	1,593	67	1,660
2002	371	1,053	166	1,590	67	1,657

Broadleaves						
	England	Scotland	Wales	GB	N Ireland	UK
1924	490	57	57	604	2	607
1947	521	106	61	689	4	693
1965	425	52	33	510	8	518
1980	519	83	64	666	12	677
1995-99	724	236	124	1,085	16	1,100
2001	728	264	121	1,113	17	1,130
2002	733	271	122	1,126	17	1,143

Table 2.6 **Woodland area by country** (source: GB 2001 and 2002 data from NIWT and FC; NI data from Northern Ireland Forest Service). Units: '000 ha

Notes:
Conifer/ broadleaf split for Northern Ireland prior to 1980 is unavailable.
NI and UK data for 1924, 1947 and 1965 are estimates.

2.3 Drainage

On a field-scale, ridge and furrow was one of the oldest practices to ensure a modicum of land being moderately well drained, especially applicable to clayland areas, where it exploited the natural properties of the clay to dispose of surface water by runoff. It has been a natural progression to install underground channels in the furrows and thus was launched the tradition of a local drain spacing that survived as an influence for centuries. The materials used for early drain channels were those most easily obtained, so a variety of drain types evolved, utilising stones, bricks, straw ropes or hedge trimmings for example. On the heavier clays, ingenuity was employed to exploit the natural properties of the soil for plasticity and cohesion to produce channels within the subsoil – the mole channel. Permeability aids and moling have remained as key features of drainage practice ever since.

Ditches were the primary drainage system as more land became enclosed and managed, but distinctive patterns of underground drainage developed as landowners came to recognise different drainage problems. Elkington is well recognised for his work on specifically sited, deep drains to intercept spring seepage water (Johnstone, 1801), whereas Smith of Deanston takes credit for a uniform pattern of close spaced drains covering whole fields (Smith, 1837). The economic production of clay pipes on an extensive scale by around 1800 allowed his principle to extend to much of the country.

A 'gridiron' layout of parallel drains became common for flattish land, whereas the 'herringbone' layout was developed for sloping land to intercept the 'downhill drift' of water. Heavy land often had drains at about 750mm (30") depth and a spacing of 1 rod (5.5yds/5m), whereas in deep, open soils, 1.2m (4ft) depth by a chain spacing (22yds/20m) would be more likely. The lower the permeability of the soil, the closer and shallower it was found necessary to lay the drains and the less feasible it became to use greater depth to justify wider spacings. Water tended to move within the topsoil until it found the more permeable soil over a drain; thus, the heavier soils justified drains at 600-750mm depth (24-30") by spacings of 1, 2 or 3 rods. Mole drainage had become the standard for the major clay formations and most of the principles were well documented by the time of Arthur Young's *"General View of the Agriculture of the County of Essex"* (Young, 1807). Thus, a pattern developed of different drainage methods, applicable to those parts of the country where they seemed best suited, and by the 1880s most of the agricultural land requiring drainage had been so serviced.

The pre-eminence of nitrogen in agriculture as 'a panacea' from about 1890 and the Depression years to 1939 meant that little underdrainage, or maintenance, had been carried out since the 'Golden Age' of Victorian farming. The 'War-Ags' were therefore faced with a massive programme of maintenance as a priority, to realise the potential of agricultural land and with little drainage activity in the previous 50 years, it was to the principles and examples of their Victorian predecessors that they had to turn for knowledge. Hence, the design parameters and importance of local drainage traditions from the 18th and 19th centuries were still key factors in the design of drainage schemes, for at least the initial post-war period. It was only with development of research into soils and crops, and the technological advances with machines that brought about significant changes in drainage design and practice. MAFF grant-aid provided the impetus and means to the volume of drainage installation that followed over the next 30 years.

The collective drainage opinion of this earlier installation is that not much of it would be considered as very effective for today's agriculture. The high intensity drainage activity of the 1840–1870 'High Farming' period often involved 50mm (2") pipes laid 3-4ft (0.9–1.2m) deep, straight down the slope at close spacing, with no permeable backfill material. Some of these schemes may still be providing a drainage benefit on permanent pasture, but most will have fallen into neglect (blocked outfalls for example), or been replaced by a more modern design/installation, especially for arable production. Some deeper drains for watertable control or spring line interceptor drains may still be effective after 200 years, but the demands of modern agriculture and the burden placed on the soil indicate that newer systems, permeability aids and secondary soil treatments are frequently needed for full effectiveness.

Field drainage in the 1950s & early 1960s

The 'War-Ags' and their successors of County committees operated a contracting service of drainage operations until about 1958, involving a range of excavators (over 300 machines nationally in the 1950s) for both ditching and underdrainage works. Priority was given to ditching works to both remove surface water and relieve existing, blocked drains (from the Victorian age or before) as a means of getting land back to better production. Even in the late 1950s, work was still involved in 'restoration' of land neglected by generations and compounded by natural disasters such as the 1947 flooding of whole swathes of agricultural land.

Underdrainage work in this period was very slow - a rate of 'a chain a day' would not be uncommon - so even if figures were available, total drainage per annum would more likely be in hundreds of hectares at best, rather than thousands. The ADAS estimate for the 'busy' drainage county of Lincolnshire was about 40 acres (16ha) installed per week for the drainage season, which did not include growing crop periods or wet weather, when no drainage was installed. Even with the development of specialised machines for trench excavation, drain laying of the clayware pipes was still generally by hand. The majority of the field drainage work was undertaken in the eastern counties, for the simple reason that intensive underdrainage is mainly associated with arable farming, and farm economics supported the use of effective drainage.

Drainage design was still largely based on the local traditions such as 'the 7 yard rule' in Cumbria, although the chain (20m) spacing was becoming more standardised as a compromise between the high costs of closer spacings and the wider intervals for true moling schemes. Upland areas like Durham & the North East, the South West and parts of the Pennines tended to work on 12-15yd (11-14m) spacing, although topography would play a key part in positioning in depressions for example. There was very little in the way of secondary treatments - the soils and therefore tradition, did not warrant moling and many farmers disliked the concept of subsoiling because it so churned up the surface that re-seeding was felt to be necessary. Permeable backfilling was rarely used – the more open nature of the backfilled spoil in the drainage trench was relied upon to provide the permeability access for water into the drain. The fact that this more permeable zone was evident for several years by crop growth or greener lines in dry periods gave credence to this design criteria - ‘it seems to work, so why change it’ attitude.

Eastern England generally relied upon mole drainage with pipe drain spacing depending upon the quality of the clays to retain a stable channel, e.g. 70-90m on the glacial tills (Boulder clays) of Northamptonshire down to 30-40m on the less calcareous clays of say Nottinghamshire. Moling depth had become fairly standard at 525mm (21”) at around 2m (6ft) centres. The mole drainage schemes relied more on the application of permeable backfilling materials to the pipe drains, in the form of straw initially, and then clinker or gravel, if locally available and acceptable in cost. Re-moling was on an ‘as and when’ basis rather than a regular pattern of say 3-5 years, but there does seem to have been a commitment to maintenance.

MAFF were involved in the restoration of opencast coal sites and a generally standard drainage design of 20m spacing was developing with gravel for permeable backfill and moling, which was considered to be a very intensive scheme at that time.

Although MAFF were paying grant-aid on the drainage schemes, it does not seem that a ‘Government’ design emerged to influence installations. Spacing, depth and the use of permeability aids were still largely a matter of local tradition and ‘what the farmer wanted’. The cost of the drainage, even with the grant-aid, was a key factor in whether the farmer drained or not, and the intensity of a scheme if he did. Because of the difficulties in proving the benefits of drainage in economic terms (as opposed to nitrogen applications for example), it was always felt that drainage was the first item to be dropped in times of economic hardship and the last to recover, irrespective of the drainage need in terms of soil or crop factors.

Field drainage in the late 1960s - early 1970s

A number of factors had a significant influence on field drainage in this period. These included the first use of plastics pipes, the onset of a co-ordinated research programme to underpin MAFF drainage design standards, increasing conversion from grassland to arable and the Strutt Report (Strutt, 1970), which followed the wet winter of 1968/69.

Plastics pipes were first accepted for grant-aid in 1964 and they paved the way for a significant expansion in the mechanisation of the drainage operation, including the trenchless method of installation. Costs of material handling declined and work rates accelerated times over, so that in conjunction with generous rates of MAFF grant-aid (to encourage food production), drainage became an important element of soil and crop management.

Research into drainage, led by MAFF's own internationally renowned Field Drainage Experimental Unit at Cambridge, proved the benefits of drainage, the gains of applying permeable fill to drains, and the benefits of carrying out appropriate secondary treatments like moling and subsoiling. Schemes became more scientifically designed, with a greater concentration on soil treatments to assist permeability.

The political/economic climate for agriculture encouraged the change from grassland to arable, especially of the 'marginal' land, and grassland was managed more intensively with silage overtaking hay. This increased burden on the soil favoured more drainage activity.

The exceptionally wet autumn of 1968/9 produced the Strutt Report (Strutt, 1970), *"Modern Farming and the Soil,"* which had a profound influence on cultivation techniques and led to a range of developments into subsoiling methods and equipment for soil management. Effective drainage was identified as an essential element for many soils in achieving the objectives and aspirations of the Strutt report.

Drainage need

MAFF's Land Drainage Service carried out a National Survey of Drainage Need in 1968/9 in recognition of the increasing demands placed on soil by modern farming and to update existing information on the drainage condition of the 27.2m acres of agricultural land. Bailey Denton (1881) had indicated to the Lords' Commission on Agriculture in 1880 that 15.5m acres needed drainage, of which 7.5m would be very well worthwhile to drain. He estimated that some 3m acres had actually been drained, but sales of pipes suggested that this could have been as high as 10-12m acres. An internal MAFF study of the 1950s, based on geology, produced an estimate of 14m acres in need of drainage improvement.

The 1968/9 survey was based on a 5% sample and involved the classification of all agricultural land from a geological base on each of 301 O.S. 1:10,560 maps. Some 1.4m acres were actually assessed by Drainage Officers (DWSOs) and allocated to a category according to drainage conditions. The individual map results were processed and raised statistically to produce regional and national data. They were considered to be statistically robust to within 10% and to give a good picture of the drainage condition of the agricultural land of England & Wales. The results of the 1968/9 survey are given in Table 2-7.

Land Classification	Estimated area in m acres
Drained by Grant scheme since 1939	1.7
Naturally free draining	10.5
Satisfactorily drained by pre-1939 systems	5.3
Capable of improvement by drainage	7.1
Unlikely to be economically drained	2.6
Total	**27.2**

Table 2.7 Land drainage classification from National Survey of Drainage Need 1968/69

The ‘Old’ category of pre-1939 drains is significantly large at 5.3m acres. Analysis of the results shows that much of this land lies within the north and west of England, where steeper slopes and permanent pasture may account for the perceived continued effectiveness of old drainage systems (e.g. self-cleansing velocities and stable soil structure). If 10-12m acres were drained in 1840-90, it is not unreasonable to find that 5m were still in working order in these areas, 80-100 year later. Similarly, the results show the predominance of new drainage under grant-aid in Eastern England - 0.68m acres out of a national total of 1.7m acres - and also the highest requirement for acres in need of improvement at 1.57m acres, with a very low level of effective old drains at 0.40m acres.

With the benefit of hindsight, we would have reservations about the survey in terms of its assumption that fields drained under grant-aid since 1939 were satisfactory. Current opinion would cast doubt on the exact effectiveness of schemes installed in the 1950s - 60s, without permeable fill and no secondary treatments. Secondly, the Geology sheets did not record Drift material unless it exceeded 1m thickness, so a Chalk formation, for example, with about half a metre of Boulder Clay cover could have been classed as free draining. Hopefully, the survey assessment would have corrected this possible anomaly, but it illustrates the need for circumspection in interpretation of the results, especially below national level.

The ‘considered drainage opinion’ is that the total of 7m acres requiring drainage improvement was probably dependable as a minimum national area need in 1969. Whether all the drainage activity that followed in the next 15 years made significant inroads into this total, or only kept pace with deterioration of existing systems, is open to an element of conjecture. With all the benefits of modern equipment and materials, the 250,000 acres drained per year in the 1970’s was still below the annual peak of the 19th century drainage mania. The consensus of opinion is that the pattern of drainage activity revealed by the drainage grant statistics (known as the FCG3UD data) of 1971-85 would very much mirror what was happening post war, i.e. the predominant drainage activity was still in the arable areas of Eastern England.

The FCG3UD data: 1971 - 85

The returns from this grant-aided drainage period covered most of the underdrainage proposed in the country on agricultural land, so can be considered as a very accurate reflection of the overall pattern of drainage activity, and the most detailed source of technical information on the drainage schemes installed.

The data cover applications for grant-aid rather than the area actually drained. There was a particularly high rate of drop out in 1974 when a number of applications were submitted in advance of a reduction in grant aid, but the work never completed. The ‘drought’ year of 1976 also revealed a significant drop in applications. These factors indicate the importance of the rate of grant, and prevailing weather conditions, as factors in farmers’ decisions as to whether to drain or not, rather than just a soil-type/cropping requirement decision. This variety of influences on the drainage decision mirrors the historical perception.

Analysis of the data clearly shows the continuation of the trend for concentration of drainage activity on the clay soils of Eastern England and the predominance of that area for moling schemes. As to be expected, clay soils with their restricted permeability, show in some 75% of all schemes. Some two thirds of drainage problems in the SE quarter relate to impermeable subsoils, whereas this drops to below 50% for most of the rest of the country. This does not correlate to permeable backfill use, as many springline schemes of the South West and Wales would regard this as an essential addition to the scheme.

Permeable fill use remained fairly constant for around 60% of schemes throughout the recording period and this may seem slightly surprising in the light of the significant rise in secondary drainage treatments from around 30% in 1971 to nearer 50% by the end of the period. As had been found in the 1950s, the clays on the older rocks of northern and western England were not particularly favourable to effective and stable moling, and heavier rainfall may have discouraged subsoiling. Plastics pipes and the trenchless technique of installation continued to grow in popularity, but they did not have any significant bearing on drainage design.

The national figure of only some 4% of drainage problems being attributed to the failure of old drains also seems low, given the fact that most fields being drained already had at least one historical system in existence. The instructions for completion of the data sheet were that the predominant drainage problem should be recorded, so impermeable subsoils, or springlines, would take primary place on most forms. The figure is not available as to what percentage of schemes had old drains present in some form or other, but the assumption was that a new scheme was considered essential for full drainage effectiveness. Many of the schemes no doubt involved the drainage of fields which had been recorded as satisfactorily drained by old drains in the 1968/9 survey and a proportion were repeat drainage of fields with a grant-aided scheme since 1939. This is borne out by comments from older ex-MAFF Drainage staff that the earlier schemes up to the 1960s were not always considered effective for the modern demands placed on the soil in the 1970s and 1980s.

Overall historical context

Virtually all fields requiring drainage for effective farming will have some form of drainage system installed and many will exhibit several attempts at underdrainage over the last 250 years. This statement is consistent with the Report of the Land Drainage Legislation Sub-Committee of the Central Advisory Water Committee, (MAFF, 1951). In relation to the demands placed on soil by the intensity, scale and size of modern farming, considered drainage opinion would be that it is generally only those schemes installed within the last 40 or maybe 50 years which could be considered as having the potential to deliver effective drainage.

Even then, a degree of caution has to be injected because the standards of maintenance in terms of ditch clearance, free outfall discharges and the necessity/frequency of secondary treatment renewal to maintain drainage status are not clear in their completion. Most of the older schemes will still be contributing to the drainage effect and running water for parts of the year, thus posing a potential threat to the dispersion of diffuse pollution to watercourses, but their input cannot be regarded as significant to the full effectiveness of drainage purposes for the modern era. Within this comment is therefore contained the conclusion that the FCG3UD data may be taken as a significantly accurate guide to the current status of modern effective drainage in England & Wales.

The 1960s saw a significant change in the drainage activity of England and Wales with the increasing use of permeable backfill in durable materials such as gravel, and the development of subsoiling as a secondary treatment to assist soil drainage. This had the impact of generally allowing the wider spacing of pipe drains over much of the country from the local traditions of such as 'the 7 yard rule' to a more uniform approach of 'chain apart, permeable fill and subsoiling/moling'. Schemes varied around this basic 20m/chain spacing, with 10-12 yds (half chain) or 15-17 yds (three-quarters chain) where flatter areas, steeper slopes and/or doubts about subsoiling effect were involved; or chain increments to 2, 3 or 4 chains for moling schemes. Permeable fill would be used where soil permeability was restricted, springline interception was involved, or old drains needed to be incorporated. The variety of the 19th century, and the transitional efforts of the 1950s, were replaced by a more uniform drainage pattern in the 1970s.

3. State of current farming and key impacts on flood generation

Current farming practices are reviewed in this section, based largely on the reviews and data in Section 2, and detailed assessments are made of the following:

- cultivation and soil characteristics
- soil structural degradation and compaction
- cultivation and runoff
- grassland, maize and forage production and runoff
- poultry and runoff
- agricultural drainage effects on runoff
- field-scale effects of drainage
- moorland and peatland drainage
- moorland grassland and grazing

Flood mitigation measures and practices work by using or affecting the interactions and processes described in these assessments.

3.1 History

As summarised by the Section 2 review, important changes have taken place in UK agriculture. Modern agriculture is largely a consequence of the 1947 Agriculture Act, which sought to attain self-sufficiency in food production. This trend was accelerated with the country's accession to the European Union (EU) in 1973. Crop price maintenance together with capital grants and subsidies to encourage investment in agriculture led to an increase in the arable area. The use of machinery in agriculture increased significantly. This has in part helped a move towards larger farms. Between 1949 and 1999 there was a 35% reduction in the number of farms (Defra statistics). In 1949 only 1% of farms were greater than 200ha in size. By 1999 this had risen to over 6% (Robinson & Sutherland, 2002).

At the same time, however, there was increasing research conducted and a general move towards more sympathetic farming systems in some parts of the industry. Of note was the introduction of ICM, IFM and Organic Farming. Whilst these more environmentally friendly farming systems may have immediate benefits to wildlife, the effects on hydrology and flood runoff have not been researched.

3.2 Impacts and other relevant data

- Cereals - the change from spring to winter-sown cereals. In 1962, the percentage of winter-sown wheat was 70% and percentage of winter-sown barley was 10%. By 1975, these percentages were 90% and 10%

respectively. By 1998 these percentages were 97% and 65% respectively. This may have increased the risk of runoff due to bare cultivated soils at the time of early winter rainfall;

- Heavy pressing following earlier drilling for oilseed rape may cause problems to runoff; severe compaction on headlands is now evident;
- Heavy machinery harvesting of maize in September/October, especially by contractors who do not take account of soil conditions, combined by drilling and harvesting up and down the slope may lead to enhanced runoff. Also, the lack of cover in the summer makes maize fields susceptible to erosion in thunderstorms;
- Potatoes - the availability of irrigation means that potatoes are now increasingly grown on lighter land and on sloping soils - this can create runoff/erosion problems. De-stoning and ridge and furrow patterns may concentrate water movement;
- Sugarbeet - changes in harvesting means that field/soil trafficking can occur over the winter period with possible soil damage. Contract harvesting with heavy machinery may cause runoff problems;
- Carrots - irrigation leads to late harvesting (January-March) which may cause compaction;
- Cattle and grassland - cattle grazing areas are often in high rainfall areas; with extended grazing this encourages trampling and compaction leading to reduced infiltration;
- Sheep and grassland - the same problems as seen for cattle apply to sheep, however, the dramatic increase in numbers, especially in the uplands, is seen as a cause of compaction and increased runoff;
- Pigs - the increased use of outdoor production methods have led to loss of vegetation, and an increase in compaction and runoff;
- Cultivation with chisel or tine plough is now more favoured than mouldboard ploughs, because of reduced draft (machinery pull) requirements, resulting in less soil disturbance. Integrated Crop Management and Integrated Farming Systems encourage the use of minimal tillage techniques (Game Conservancy Council, *Pers. Comm.*; LEAF, *Pers. Comm.*). Harvesting is now quicker as several operations (e.g. harvesting, binding and threshing) take place in one stage;
- Field size has increased through the removal of hedgerows, a trend that accelerated in 1960's with the widespread use of tractors and combines. In pastoral Somerset the average field size increased from 5.5ha in 1945 to 9.5ha in 1995. In arable Cambridgeshire, this increase was 6.5ha to 16ha. In 1945, hedgerow length in England and Wales was about 970,000 km. By 1990 it had decreased to about 400,000km;
- The widespread use of pesticides, especially pre-emergent herbicides, now allows continuous arable cropping (especially in eastern England), rather than rotations including root crops and grass leys, fallowing or tillage operations to suppress weeds;
- Continuous use of sandy, sandy loam and loamy sand soils of northern Europe for arable farming is resulting in soil degradation. The organic content of the soils has decreased following the removal of grass leys from

the rotations. The soil is more prone to degradation by raindrop impact (Morgan, 1986);

- Overall, compaction has been enhanced by more intensive use of the land, increasing field size and heavier machinery. The pattern of compaction by tractor wheels depends on tyre pressure, tyre width, vehicle speed and the effects generally extend down to the depth of the soil loosened in the previous tillage. Pidgeon and Soane (1978) found that combine harvester wheels compacted a sandy loam to 300 mm depth if the soil had previously been deep ploughed, 180 mm with mouldboard ploughing, 150 mm with chisel ploughing and 60 mm with no tillage. Compaction reduces porosity and infiltration. Martin (1979) found that one pass of a 3 t tractor wheel reduced the infiltration capacity on a sandy soil from 420 mm/h to 171 mm/h. After 10 passes it was further reduced to 83 mm/h. The reduction in infiltration capacity would increase the likelihood of surface runoff, especially in tramlines. Compaction effects can be rectified by tillage at appropriate soil moisture conditions;
- Set-aside has been available to farmers since 1992 and is increasing in extent. Nowadays about two thirds of set-aside land in Britain is rotational, leaving an overwinter stubble.

3.3 Environmentally developed agricultural systems

Integrated Crop Management (ICM)

ICM combines good farm husbandry, which is already done by many farmers, with a whole farm long-term approach that reduces the need for agrochemicals and takes the impact of farming practices on the environment into consideration. Each farm is different so the programme is tailored according to location, soil-type, markets, storage facilities, labour skills, farm layout and environmental vulnerability. There are some key management components within ICM (see below) that must be used together to develop an integrated system, but the system must remain flexible to be workable in the long term.

ICM provides a way to ensure profits and protect the environment at a time when changes in Britain's agricultural landscape, through intensification and increased production, have come under increasing public criticism. Research in the 'LINK Integrated Farming Systems' project, concluded that the integrated system was equally profitable to conventional farming, with the first wheat crop in the rotation, the spring barley and the oilseed rape returning better profits in ICM. This was achieved through a 26% reduction in pesticide use in ICM, peaking at 41% pesticide reduction in first wheat. Although yields were sometimes lower in ICM, as long as this made sufficient savings, then profitability was unaffected.

Many different practices have been tested within ICM: delayed drilling of wheat; mechanical weeding; low disturbance cultivation ('non-inversion tillage'); luring pest species out of the main oilseed rape crop by planting an earlier flowering variety around it; flower borders to encourage aphid-eating insects; lower pesticide inputs combined with monitoring problems; avoiding broad-spectrum pesticides; lower nitrogen inputs.

Crop rotation. The cornerstone of any integrated system. It uses at least four different crop types through a minimum five-year rotation. A longer rotation means more crops, which reduces weeds, pests and diseases and ensures a good nutrient balance. A diverse crop rotation spreads the workload, the risk of poor incomes, and minimises the impact of any one crop on the environment. Including some spring-sown crops can bring extra benefits, because where stubbles are left over the winter, they provide cover and food for farmland birds such as grey partridges, skylarks and corn buntings. A mosaic of different crops on a farm creates a diverse range of habitats.

Soil cultivation. A healthy, well-structured soil ensures that crops establish and grow well. Match the cultivation method to the crop and soil-type. Establish crops by using methods that avoid disturbing the soil surface - either by direct drilling into the stubble of the previous crop, or by cultivating the surface only enough to allow drilling. This saves energy and keeps organic matter near the surface. It encourages organisms like earthworms, helps retain soil moisture, prevents nitrates and phosphates from leaching out, and encourages beneficial invertebrates, which control pests and provide food for birds. Such 'non-inversion tillage' is not always suitable, especially on heavy land where grass weeds are plentiful. In this case, ploughing may be necessary in the rotation to control weeds.

In summary, there are many techniques within ICM that could be employed to reduce input costs. The ones that are used will be those that are most suitable to the site, and farm management system. For example, delayed sowing would be suitable for only a limited number of farms or fields under Northern Ireland conditions. Table 3.1 lists some of the more common ICM techniques and the inputs that they assist to reduce.

Integrated farm management (IFM)

The principles of Integrated Farm Management are:

- a commitment to good husbandry and animal welfare
- efficient soil management and appropriate cultivation techniques
- the use of crop rotations
- minimum reliance on crop protection chemicals and fertilisers
- careful choice of seed varieties
- maintenance of the landscape and rural communities
- enhancement of wildlife habitats
- a commitment to team spirit based on communication, training and involvement

Organic farming production

The UK organic market has increased rapidly over recent years with growth rates of 30-50% per annum; see Tables 3.2 and 3.3. Sales in 2000-2001 amounted to £802 million, up by 33% on the previous year. 2001-2002 sales are predicted to be up a further 20% to over £950 million. By the end of 2001 organically managed land accounted for 2.5% of all English farmland, over the whole UK 3.9% is under organic management. Secretary of State, Margaret Beckett MP, proposed that the sector could experience a three-fold increase - taking it from 3% of UK agriculture to around 10%. Others propose a more ambitious target of 30% of production and 20% of the retail food market organic by 2010.

Input	ICM Technique
Seed	Early sowing of winter cereals Varieties with high tillering capacity Use of high vigour seed Sowing in good seedbed conditions
Fertiliser	Adoption of good rotation and inclusion of legumes Use of organic manures Regular soil sampling Calibration of spreaders Matching of rate to yield Adoption of non-inversion tillage
Herbicides	Delayed sowing of winter cereals Use of stale seedbeds Inter-row cultivation Ploughing to control grass weeds Increased seed rates Control of weeds when small Assessment of weed species and population to target only the most competitive and/or numerous weeds Target less aggressive weeds elsewhere in the rotation Adoption of a rotation that minimises weed pressure
Fungicides	Delayed sowing of winter cereals Sowing resistant varieties Use of weather-based disease forecasting models Assessment of diseases and levels to apply the appropriate rate at the optimum timing. Employ decision support programs Adoption of a rotation that minimises disease pressure
Insecticides, molluscidides, etc	Monitoring of crops for pests and use of thresholds to assess need for application Use of pest forecasting systems Delayed sowing of winter cereals Use of products which are safe to natural predators
Plant Growth Regulators	Use lodging resistant varieties Match fertiliser rates to yield
Energy	Adoption of non-inversion tillage Use of minimal pass systems

Table 3.1 ICM techniques

Region	Management	April 2000	April 2001	April 2002
England	In conversion	110,000	132,000	101,088
	Organic	40,000	87,200	145,600
	TOTAL Organically managed	150,000	219,200	246,688
UK	In conversion	307,617	312,482	270,950
	Organic	104,232	240,000	458,600
	TOTAL Organically managed	411,849	552,482	729,550

Table 3.2 Organic and in-conversion land in England and UK (source: DEFRA, UKROFS and Certifying Bodies).

Land use	England			UK	
	Organic Ha 2002	% of total organic 2002	% of total conventional 1999	% of total organic 2001	% of total conventional 1999
Rough grazing & perm pasture	73,125	50.5	40	81	57
Temporary ley	44,658	30.8	7	9	7
Arable	19,143	13.2	42	7	28
Horticulture & potatoes	3,633	2.5	3	2	2
Woodland	1,018	0.7	-	-	3
Orchard	821	0.6	-	-	-
Set-aside	2,533	1.7	5	1	3
Total	144,931	100	100	100	100

Table 3.3 Organic and conventional land use in England and UK (source: DEFRA and Certifying Bodies).

In December 2001 (UKROFS data), almost 4000 organic producers managed 680,000 Ha of land organically (39% of this is in conversion and 61% fully converted) - equivalent to 3.9% of UK farmland and an increase of 29% year-on-year. The majority (90%) of organically managed land is grassland, most as rough grazing and permanent pasture. Overall, England accounts for 32% of organically managed land (converted and in conversion) in the UK; Scotland 60%, Wales 7% and NI 1%.

The area of fully converted land increased rapidly during 2001 as conversion completed on large areas of land entered into the new Organic Farming Scheme (OFS) in 1999, by December 2001 almost 50% of the organic area in England had converted through the OFS. In April 2002 a total of 1,750 OFS agreements covered 158,735 Ha. In England the area producing organic crops and livestock increased by a factor of 2.6 and in Wales by 3.4 between 2000 and 2001. This sharp rise in availability of organic products has inevitably led to real marketing difficulties for farmers in some sectors, with considerable pressure put on organic prices and leading organic producers to sell a proportion of their milk, potatoes and livestock as conventional rather than organic.

Further expansion of the sector in England will depend on and contribute to developments in Scotland, Wales and NI, as well as other countries in Europe. Most importantly, expansion must be closely linked to the development of the organic market. Effective co-operation from the producer and through the supply chain is essential to ensure security. This has been very clearly demonstrated in those sectors where a rapid increase in supply has not found an organic market.

Horticulture represents the most important organic category whilst in livestock, hill and upland conversion has been over-represented with a disproportionate rate of conversion relative to the lowland. This has resulted in insufficient availability of lowland farms able to finish the large numbers of cattle and sheep. With the overwhelming proportion of organic land in grass, and most in permanent and rough grazing, it is not surprising that there is a relative shortage of organic arable production, particularly in view of the importance of arable crops for livestock feed and human consumption. The strategic development of this sector must be carefully managed, but the potential benefits (both in terms of crop production and in provision of suitable organic farmland in a ley-arable organic rotation suited for finishing beef and sheep) could be substantial.

Although England has the largest proportion of conventional arable land in the UK (42%), organic arable production in England is significantly underrepresented (13%). However, England already has almost double the proportion of organic arable land compared to the UK whilst there is more than three-times the area of organic temporary ley.

Table 3-3 shows the different types of land use on England's organic farms. Compared with the organic-UK as a whole, England has a higher proportion of organic arable, temporary ley, vegetable crops and orchard, whilst only half of the total area of organic farmland is rough grazing and permanent pasture in England, substantially less than in the UK as a whole (81%).

The Organic standards cover all aspects of farm management to ensure a sound and sustainable organic farming system. These show that the conversion to organic could impact on hydrology through an influence on timings of cultivations.

Conversion: Most farms will first need to go through a two year conversion period where the land is managed organically, but crops and livestock may not be marketed as organic.

Soil fertility: The focus is on crop rotations and the use of animal manure and compost to maintain natural soil fertility, without the use of artificial/synthetic fertilisers.

Pest, disease and weed control: This is achieved through rotation, choice of varieties, timings of cultivations and habitat management to encourage natural predators. All herbicides are prohibited. Where direct intervention is required a small range of approved inputs like sulphur may be used in a controlled manner.

Conservation: The standards encourage the development of a healthy environment, enhancing landscape features, wild plants and animal species by, for example, maintaining hedges as an important wildlife habitat.

Livestock: The livestock standards cover livestock conversion, animal feed, housing and stocking densities, veterinary treatments and animal welfare. The emphasis is on a positive system of livestock management to maintain healthy stock and a balanced system.

Genetically modified organisms (GMOs): GMOs and their derivatives are strictly prohibited at every stage of production.

3.4 Agricultural management: effect on soil physical conditions

Effect of cultivation on soil characteristics

According to Addiscott and Dexter (1994) there are three types of cultivation operation: primary, secondary and subsoiling. Primary cultivation loosens soil and involves total or partial soil inversion for weed control or crop residue incorporation. Secondary cultivation produces further breakdown of soil aggregates to prepare, for example, a seedbed. Subsoiling may be undertaken every few years below the depth of other cultivation operations to loosen compacted or dense subsoils or to create mole drainage channels.

Cultivation causes a disruption in the physical structure of the soil and can result in the breakdown of soil aggregate size and stability (Terbrügge, 1993; Silgram and Shepherd, 1999). The soil structure resulting from tillage depends on soil-type, water content, tillage implement used and the management history of the site. Primary cultivation increases the porosity of the ploughed layer of the soil (Addiscott and Dexter, 1994). As a result of increased porosity in the topsoil the level of aeration is also elevated, leading to a generally warmer and drier soil. Ploughing does however disrupt the soil drainage characteristics, particularly the connectivity and continuity of the soil macropores which transport water from the topsoil to the deeper layers in the profile (Harris and Catt, 1999). This reduction in connectivity of the soil pores can be decreased further if the cultivation operation has created a smeared plough pan which restricts drainage or soil hydraulic conductivity below the cultivation depth. Due to the instability created in the soil aggregates by ploughing, cultivated soils tend to be more susceptible to compaction problems caused by repeated vehicular trafficking when compared to reduced cultivation systems (Addiscott and Dexter, 1994). Compaction, which can extend down to at least 0.5 m in the profile, has the effect of substantially closing down the larger pores initially, which again reduces the amount of water that can be transmitted to the lower soil layers. The soil moisture conditions at time of cultivations can have a strong influence on soil physical conditions (Silgram and Shepherd, 1999). Cultivation, especially ploughing, can cause serious compaction if undertaken when the soil is too wet.

Subsoiling and mole drainage, if undertaken when the soil moisture is not too great, greatly disturbs the soil profile by creating a large network of cracks in the soil which permit the rapid flow of water down from the topsoil towards the lower layers. Subsoiling is generally undertaken to remove problems of compaction, either at the soil surface or lower down the profile. If mole drains have been produced (usually at a depth of 0.4-0.6m) these will connect into permanent underfield drainage pipe systems which discharge directly into open watercourses. If undertaken in the right conditions mole drains can remain effective for several years.

The presence of organic matter in the soil greatly affects the stability of soil aggregates. Any cultivation operation that disturbs the soil increases the rate of organic matter mineralisation and hence decreases the organic matter content (Silgram and Shepherd, 1999). In reduced cultivation or zero cultivation systems, the amount of soil disturbance is minimised therefore providing opportunities for the soil organic matter content and the soil aggregate stability to increase.

Soil structural degradation and compaction

The review for the EA undertaken by the NSRI (Godwin and Dresser, 2003) was undertaken to identify evidence to support the hypothesis that *"The water retention capacity of soils could be enhanced by a variety of affordable measures that would make a significant difference to peak flood flows, whilst contributing to improving water quality through reduction in siltation and diffuse pollution and enhancing nature conservation and fisheries interests"*.

This work was conducted specifically in the Tone and Parrett catchment in North Dorset but contains key literature search information of general importance. The authors found ample evidence from many sources that the infiltration rates in soils in good structural condition are in excess of current typical rainfall intensities found in many parts of the UK. However, 75% of the sites examined by NSRI in the Tone & Parett catchments, and similarly in the Uck catchment, showed signs of structural degradation. At the catchment-scale, modelling suggested that improving the structural condition observed could reduce runoff at the catchment-scale between 37.5 and 70%. Within the catchment, NSRI found that the land conditions demonstrating the greatest potential of increased runoff were soils that had suffered from significant surface capping (crusting) and compaction, the former typically having infiltration values of 5 mm/hr (Holtan and Kilpatrick, 1950).

Davies *et al.,* (1973) showed that compaction caused by wheels significantly reduced infiltration to 10% of that of an unwheeled area. Young and Voorhees (1982) also demonstrated that the infiltration rate in a compacted wheel mark is zero after 100 minutes of rainfall, compared to uncompacted soil which has an infiltration capacity of 10mm/hr. These findings were supported by Edwards and Daniel (1994), who found that all rainfall ran off the surface of compacted sandy loam at 4°, when simulated rainfall at 75 mm/hr was applied.

In contrast, uncompacted grassland and woodland conditions have infiltration rates in excess of 60 mm/hr, as do soils with a high level of surface mulch, which protects the soil from capping. Tullberg (1996) reported that this can be influenced by the residue strategy of the tillage system with a combination of controlled traffic and zero tillage practices reducing runoff by 48%.

Destroying compacted layers, ensuring that soils are well drained or lowering the watertable can all improve the total soil volume available for storage in a rainfall event. Work in the Uck catchment by NSRI suggested that lowering the watertable by 0.5 m prior to the onset of a significant rainfall event would provide sufficient storage for 50 mm of water - which is more than one days rainfall for a 1 in 10 year return period event. Good drainage in grassland can, through lowering the watertable, provide storage but also increase the strength of the soil, thus reducing any compaction damage by animals.

NSRI reported that care was needed when managing the surface compaction made by wheelings, which generally ran up and down the slope. Whilst simply loosening the soil surface can increase infiltration, in the longer-term gully erosion can occur. The use of wider tyres (0.5-1 m wide) will reduce contact pressures and rutting and increase trafficabilty.

Adequate drainage, either through deep percolation or interception is seen as essential to connect to the subsurface drainage treatment; moling across wide spaced tramlines is seen as a way to intercept runoff whereas Spoor & Godwin (1981) suggested that times could be fitted behind the furrow wheel of tractors to destroy compaction created during mouldboard ploughing.

Leopold & Maddock as early as 1954 stated that improved management, including crop rotations, the sequence of planting crops, the use of mulches and other practices which improve the soil tilth were more effective in reducing storm runoff than the more readily observed practices used in the USA in particular, such as terracing, contour cultivation and strip cropping.

Effect of plough layer cultivations on runoff

Tillage can increase the roughness of the soil surface, thereby increasing the ability of the surface to store water temporarily in depressions, permitting infiltration and delaying the outset and reducing the rate of runoff (Addiscott and Dexter, 1994).

Small-scale changes occur in ploughed land surface morphology following primary cultivation of arable fields. It involves the breakdown of clods left by disc harrowing into aggregates and individual particles which, upon detachment, move freely into intervening hollows. The effect is the natural preparation of a seedbed but also a progressive reduction in the water storage capacity of the soil surface. Primary cultivation provides an exaggerated surface depression storage that is, for many soils, eroded by winter weather (rain and freeze-thaw cycles). A lack of surface storage during winter when plant cover is low will contribute to an increase in surface runoff. The presence of a plough pan or slaking (capping) of the soil surface following heavy rain will make the problem worse.

Over the growing season of a crop the soil structure changes significantly (Addiscott and Dexter, 1994). After sowing, the structure comprises individual aggregates surrounded by almost continuous macropore space. As the growing season progresses the aggregate bed settles with a loss of macroporosity. By harvest the structure is almost continuous aggregate containing mostly unconnected macropores. The extent of this pore connectivity change over the growing season is dependent on soil type.

Tramlines aligned up and down the slope, containing compacted soil, provide ready routes for surface runoff to be concentrated (Armstrong *et al.*, 1990). On more than 100 sites in the West Midlands over the last 25 years where water erosion was recorded, downslope cultivation lines and soil compaction were major factors in over 95% of cases (Reed, 1986). Ellison (1974) showed a 50% reduction in median velocity of overland flow on contour-ploughed 9-degree slopes. However, contour ploughing is rarely practical in England due to the complexities of slope angles, slope directions and irregular field shapes. Also, considerations of safety and mechanical efficiency to minimise the risk of overturning farm machinery have contributed to the lack of significant amounts of contours ploughing in the UK (Hunter, 1981).

Work by Reid (1979) on a clay soil and a rendzina (calcareous silty clay loam) showed that the surface storage in the rendzina did not change over a winter period but that the surface storage in the clay soil was significantly reduced. Other field experiments by Reid *et al.* (1990) on a number of different soil-types showed that timely seedbed preparation and deep soil loosening decreased storm drainage by as much as 40% and 63%, respectively, at least in the short term. This indicates a reduced flood hazard in the arterial waterways of catchments where soil loosening is extensively practised.

The use of detailed digital terrain models (DEMs) by Souchere *et al.* (1998) showed that for 20 of the 23 catchments studies in the intensive arable Pays de Caux region in France, the runoff from more than 50% of the catchment area were produced along the tillage direction. The tillage operation modified both the shape and size of catchments. This tillage controlled flow direction result was also found by Jetten *et al.* (2001) working in Belgium.

Brown *et al.* (1999) studied the effect of topsoil tilth on the movement of water through a macroporous clay soil to an artificial underdrainage system. The deeper finer tilth increased the water holding capacity of the soil and had a slower wetting of the subsoil than the standard agricultural tilth. The finer tilth caused a reduction in the macropore flow during the early autumn period. However, this difference did not persist over the following winter period. In contract, Speirs and Frost (1985) reported that the creation of increasingly fine seedbeds did increase erosion risk by reducing the infiltration capacity of the soil.

At the base of the tilled layer there is often a compacted or smeared surface created by the tillage operations (Addiscott and Dexter, 1994). The percolation of water through macropores or the soil matrix is inhibited by a significant decrease in the soil hydraulic conductivity at this depth. A perched watertable is created which may, under certain circumstances, cause the topsoil to become saturated and surface runoff to be generated.

On a cracking clay soil the effects of differential cultivation techniques, particularly the contrast between reduced cultivations and ploughing, can have effects equal in magnitude to the drainage effect (Armstrong and Harris, 1996). Robinson and Boardman (1988) suggested that direct drilling of autumn cereals through the stubble would maintain crop yields, whilst reducing erosion risk. However, machinery difficulties have, until recently, prevented its widespread adoption. In the last 10 years the proportion of arable land that is cultivated to depth by a conventional plough has reduced by about 30% (A Wells, *per comm.*). Minimal tillage operations are becoming more widespread in the UK. However, the seedbed is now very shallow (about 10cm depth) with a more solid matrix below. This shallow seedbed is very susceptible to saturation and the generation of surface runoff.

Whether increased use of minimum tillage techniques will reduce the overall likelihood of surface runoff and transport of sediment remains uncertain and may depend on additional local factors. A currently unpublished but very detailed study undertaken for the Austrian Government examined the role of minimum tillage from 123 published papers worldwide (Paul Withers, *Pers. Comm.*). The work found that minimum tillage had a 50% chance of reducing runoff and a 70% chance of reducing erosion but that the result was very site specific. Tramline and tillage direction may be important in influencing the likelihood of surface runoff.

Effect of changes to grassland on runoff

The lack of publications relating to grassland changes and runoff was highlighted in Section 2. However there are some references which yield information that is more germane to the present review and are summarised below. Few of them however, are from the UK, and only these and references from overseas that are relevant to our climate, cropping patterns and practices have been included.

From the literature it appears that changes in agricultural practice and particularly the increase in stocking rates that have taken place in the last decades in the UK have increased the likelihood of higher volumes of water runoff occurring from grassland. The fact that much of our livestock industry in the UK is associated with areas of high rainfall aggravates the problem further.

There is considerable economic pressure to increase the proportion of grazed grass in animal diets as this is far cheaper than using silage, hay or concentrates. Also there is a trend to extend the length of the grazing season for the same reasons and to reduce the cost of housing. These trends for increases in grazing pressure and extending the length of the grazing season result in more treading which leads to greater sealing of the soil surface with the concomitant decrease in infiltration rates and increases in surface runoff. Overgrazing also leads to the appearance of more bare patches which tend to shed rainwater quickly rather than allowing it to infiltrate.

Heathwaite *et al.* (1990) obtained data very relevant to this point. Changing land use practices may be causing the incidence of infiltration-excess overland flow to increase, particularly in intensively grazed areas. Experimentation with a rainfall simulator and runoff plot monitoring in the Slapton Catchment in South Devon showed that heavy grazing of permanent grassland resulted in an 80 percent reduction in the infiltration capacity. Surface runoff from overgrazed permanent grassland was double that from lightly grazed areas, and at least twelve times that from ungrazed areas. Additionally, the removal of the vegetation cover through severe poaching led to an increase in the rate of suspended sediment, total nitrogen, and total phosphorus delivery in surface runoff by 30, 9 and 16 times respectively. Heathwaite *et al*. (1990) commented that riparian zones are important in regulating the sediment and solute flux from agricultural land to the stream. As 60% of riparian zone land use in the study catchment was permanent grassland, heavy grazing of these areas must be minimised to avoid substantial increases in solute and sediment loads. In other related work surface runoff from heavily grazed pasture also at the Slapton Catchment was 53% of rainfall, whereas runoff from ungrazed areas of the sward was only 7% of rainfall (Heathwaite *et al.*, 1989).

Meyles *et al.* (2001) worked on a small Dartmoor catchment in Devon and found that soils associated with areas of intense sheep grazing had a significantly lower porosity, causing a reduction in hydraulic conductivity.

Mutter and Burnham's (1990) in work on plots at Wye College in Kent also concluded that runoff and erosion were very much lower in undisturbed grass than on bare soil (akin to the effects of sheep grazing). In Morgan’s work (1977), at a number of sites in mid-Bedfordshire, grass cover reduced the erosion rate to less than 2.4 t/ha per year and woodland cover to less than 0.02 t/ha per year. Most erosion took place in infrequent but moderate storms. The most important process was overland flow which, on bare ground, accounted for over 90% of the sediment removal. Soil loss was related to the quantity of runoff.

Fullen (1992) found consistently low runoff rates and insignificant erosion on grassland plots in Shropshire compared to bare soil where runoff and erosion were high, and considered that the insertion of grass strips into arable areas would reduce runoff and erosion. He also proposed that where the slope exceeded 12 degree conversion to permanent pasture would be an appropriate means of controlling runoff and erosion.

Dewald *et al.* (1996) found that hedges provide an effective and economic way of slowing runoff water reducing soil losses through erosion.

Compaction of soil by farm machinery and poaching by livestock promoted the occurrence of overland flow in some circumstances in the view of Leinweber *et al.* (2002). The removal of grass leys in farming systems has led to significant changes in soil organic matter content and this has resulted in greater soil erosion and probably increased surface water runoff (Morgan, 1986).

There are several references to the fact that, in general, grassland and in particular long established permanent pasture has a higher infiltration rate than arable crops - especially during periods of the year when the latter are bare or crusted (Holtan and Kirkpatrick, 1950). Although noted by Holtan and Kirkpatrick (1950), it is becoming more evident recently that heavy grazing has a major impact on infiltration and runoff (Table 3-4).

Soil cover	Final infiltration rate (mm h^{-1})
Old permanent pasture	60
4-8 year old pasture	36
3-4 year old pasture, lightly grazed	30
Permanent pasture, moderately grazed	24
Hay	17
Permanent pasture, heavily grazed	15
Strip cropped, mixed cover	11
Arable	10
Bare soil, cultivated	9
Bare soil, crusted	5

Table 3.4 Final infiltration rates (source: Holtan and Kirkpatrick, 1950)

Godwin and Dresser (2003) pointed out that trampling by stock seals the soil surface and greatly reduces its hydraulic conductivity. They also noted that it is no coincidence that sheep were used to compact soils in canal beds and are used in compacting soils for earth dams and roadways.

Livestock farming in north-west Europe involves a number of practices which through ill-timed use may reduce soil infiltration rates. In recent winters, lowland pastures have seen increased sheep numbers with the inevitable turbid water discharge. This is a knock-on effect from preventing overgrazing of heather woodland in ESA's. Extended grazing also provides risks of degradation of pasture (Harrod and Theuner, 2002).

During the last 50-60 years in the Netherlands, large areas of former grassland have been ploughed and used for arable production. This appears to have had some major consequences on the environment relating, for example, to mineralisation of organic matter leading to a release of nitrates and CO_2.

Equally severe however and with more immediate and dramatic effects is the increased volume of surface runoff water that can be expected as a result of converting grassland into arable production. This increase in surface runoff may be a major contributing factor to greater flooding in recent years (Ploeg *et al.*, 1999).

In Denmark, water runoff was lower in plots of pasture than for other crops (wheat, barley, barley catch crop) (Sibbersen *et al.*, 1994).

Ground cover was the critical factor determining runoff levels in plot work in New South Wales. When ground cover exceeded 75%, runoff was slight (Lang, 1979).

Two American authors, Trimble and Mendel (1995), comment on much relevant information in their review paper relating to the cow as a geomorphic agent. The following are extracts from their review.

"Cows are important agents of geomorphological change. On the uplands, heavy grazing compacts the soil, reduces infiltration, increases runoff, and increases erosion and sediment yield. However, light and moderate grazing have effects that are much less significant. In riparian zones, grazing decreases erosional resistance by reducing vegetation and exposing more vulnerable substrate. Trampling directly erodes banks, thus increasing turbulence and consequent erosio.

Most landscapes are composed of mostly upland slopes and it is here that cattle have perhaps collectively their greatest effects. They directly reshape the earth, compact the soil and cause increased runoff, sometimes transforming the runoff regime from variable source area to unsaturated (Hortonian) overland flow. They further weaken biological resistance and trample and loosen soil, changing its susceptibility to both water and wind erosion.

The direct force of cattle hoofs reshapes the land. That force is often conceptually underestimated because it is conceived as static, i.e. the mass of the cow (typically 400-500 kg) divided by a few cm^2 of basal hoof area. But in the movement of a cow, that mass is often transferred to one or two hooves and there is acceleration in the movement. Using a mechanical simulator, Scholefield and Hall (1986) calculated that a 530 kg cow would exert 250 kPa of vertical stress while walking on level ground. However, the process is best seen and most effective when a cow is climbing a steep slope. Then, the mass is often concentrated on the downslope rear leg which propels the animal some distance upslope. The most common manifestation of direct force is the path or trail. Because the trails are less permeable (from compaction and crusting: Rostagno, 1989) and because they conduct water, they may erode to larger proportions (Hole, 1981) even under "light" grazing (Naeth et al., 1990). Cooke and Reeves (1976) speculate that concentration of runoff along such trails could help initiate downslope gully development and the work of Rostagno (1989) would appear to support such a suggestion.

Removal of phytomass by grazing and lessened phytomass production can reduce fertility and organic matter content of the soil. Soil aggregate stability is decreased and the surface sometimes becomes crusted. Proportion of bare soil appears to correlate well with surface runoff (and sediment yield) (Copeland, 1965; Lusby, 1970; Branson et al., 1981; Thurow et al., 1986; Warren et al., 1986; Takar et al., 1990; Bari et al., 1993).

Although the literature is very sketchy, it appears that fauna ranging from earthworms to moles have more difficulty surviving in the impacted soil condition resulting from heavy grazing (Hole, 1981; Abbott et al., 1979).

Lusby (1970), working in western Colorado, found that runoff from a grazed watershed was 30% greater than that from an ungrazed watershed. Rauzi and Smith (1973) report that infiltration rates varied with grazing intensity on pastures in northeastern Colorado. Under "light" to "moderate" grazing, infiltration rates were 5.6 and 5.9 cm h^{-1}, respectively, of which about 30% of the total water infiltrated within the first 15 minutes. Under "heavy" grazing, the infiltration rate was 4.8 cm h^{-1}. Usman (1994) also found that infiltration rates decreased substantially under "moderate" and "heavy" grazing and he attributed these reductions to changes in soil structure. It will be observed that there is a general decrease of infiltration capacity with grazing intensity, but there is also large variance about all of the means.

Branson et al. (1981) cite several studies which investigate the recovery of soil infiltration rates with the cessation of grazing. Hydrologic recovery was evident within 3 years on pastures in southwestern Wisconsin, within 4 years on sandy loam soil in Utah, within 6 years on ponderosa pine-grassland and within 13 years on grassland locations in Colorado.

Overgrazing alters streambank morphology by creating false, setback banks (Kauffman and Krueger, 1984). A hoof can actually shear off slices of bank material ≤ 10 cm thick, pushing them toward the stream.

The net results of grazing riparian areas, can be both (1) direct modification of stream channels and banks and (2) reduction of resistance to erosion by higher flows which promotes channel erosion. Grazing on riverine and upland areas usually go hand-in-hand so that riverine erosion is increased by the enhanced runoff regime from grazed upland areas."

Annual runoff and sediment loss from a pastoral watershed in Ohio was greatly reduced (from 10% of precipitation to 2%) when animal grazing frequency/intensity was restricted to summer only grazing (Owens *et al.,* 1997).

In two prairie situations in Colorado, light, moderate and heavy grazing was 10, 30 and 60% of simulated rainfall. When livestock were removed runoff fell to 5, 18 and 30% for the three previous grazing intensities respectively (Frasier *et al.*, 1995).

In Winconsin, Sartz (1975) found that runoff from pastures varied with grazing intensity. Runoff from pastures reduced greatly when grazing ceased.

In Hofmann and Ries (1991) work in North Dakota they had treatments which included reclaimed heavily, moderately, and lightly grazed pastures; reclaimed burn; reclaimed ungrazed; native grazed; native burn; and native ungrazed runoff plots. Total vegetative dry matter was the most important factor explaining runoff. Vegetation and ground cover were strongly related to soil loss and runoff factors. They reckoned that vegetation and surface soil factors were of major importance in explaining soil erosion on rangeland compared to subsoil factors generally associated with soil erodibility on crop land.

Srinivasan *et al.* (2002) instrumented a grass hillslope in Pennsylvania and showed in their analysis of surface saturation and surface runoff data that not all surface saturation areas produced surface runoff that reached a stream. Emergence of subsurface flow to the surface after rainfall periods appeared to be a major flow process.

Lindstrom *et al.* (1998) investigated the effect of using a mouldboard plough, a chisel plough and no-till on the infiltration characteristics of an alfalfa/brome grass sward and compared this with carrying out no cultivation. Water runoff from the mouldboard ploughed treatments averaged 24 and 66% of the applied rainfall, but only 3% for the no-till area. No runoff was measured from the grass soil.

Elliot *et al.* (2002) working in the Antipodes used small rainfall simulator plots on a ryegrass/white clover sward to study the impact of intensive grazing by cattle on soil erosion and nutrient loss. Treading resulted in increased runoff which resulted in greater sediment loads being produced because a large volume of sediment-laden runoff was produced. The increase in water runoff was attributed to a decrease in hydraulic conductivity which varied linearly with the proportion of bare ground. Treading increased the area of bare ground and this resulted in greater concentrations of sediment in the runoff. Hydraulic conductivity was approximately halved on areas of bare ground.

In their work using a large tilting flume Ghadiri *et al.* (2001) and Ghadiri *et al.* (2000) also found that the bulk of the sediment load was deposited up slope of the strips of grass or rows of nails that they studied. They do not appear to comment however on any impact that the strips had on the volume of water runoff.

In rainfall simulation studies on a red-brown earth in southern and western Australia heavy grazing of wheat stubble sites increased runoff and soil erosion from simulated rainfall areas - 1.0 - 8.3 t/ha on grazed areas and 0.1 - 0.7 t/ha on ungrazed (Malinda, 1998). Removal of grasses in two successive growing seasons compared with grass retention increased surface runoff from 15 to 30-60% of rainfall applied.

Rankins *et al.* (2001) tested the effectiveness of a range of grass species for reducing sediment and herbicide losses in runoff. Some of the grasses greatly reduced total runoff volume compared to bare soil and there were some differences between the grass species in their effectiveness.

Hairsine and Prosser (1997) reviewed the impact of perennial grasses in reducing nutrient movement with agricultural landscapes in Australia. They were of the view that the cover provided by grass had a varying effect in runoff rates, but there was a consistent rapid decline of soil erosion rates with increasing cover levels. They also quote Rutherford *et al.* (1996) as saying that grass cover also reduces flood peaks by increasing the time it takes water to reach valley bottoms.

Burch *et al.* (1983) found that soil permeabilities in Australia (central Victoria) were around half of those in forested areas. Large water discharge volumes were generated in a grassland catchment area whereas forested areas yield little runoff. Differences in permeability accounted for more of the difference between grass and forest areas than did topography. The relatively impermeable grassland depression areas generated most of the runoff.

Effect of maize production on runoff

There are many references, nearly all from overseas, relating to runoff from maize crops. The underlying problem is that because maize is particularly sensitive to competition from weeds, fields in which maize is grown are usually treated with broad spectrum herbicides (e.g. atrazine and bromoxynl) and this results in the soil surface between and within rows being virtually devoid of vegetation. There is therefore little plant cover to retard runoff. The situation is made worse in the UK because maize is often grown on the same field for several years in succession. Consequently from the time the crop is harvested (September/October) until the following crop establishes (April/May) there is virtually no plant cover at all. While the crop develops during the early growing season (May through June) there is very little plant cover. There are, then, opportunities for major surface water runoff and erosion events to happen. Furthermore, the crop is often grown in the wetter, western part of the UK, where high rainfall events occur more frequently. Serious local and downstream flooding events occur.

These problems are further exacerbated by a number of factors:

- The crop is usually grown up and down any slope rather than across it so that the harvesting machinery can cope. The harvesting machines, especially the trailer collecting the chopped crop, are heavy and slew sideways on anything other than a shallow slope. Drilling and then harvesting the crop up and down the slope results in there being few barriers across the slope to retard runoff. Worse still the tractor and machinery wheelings act as drainage channels;
- The crop is nearly always harvested by contractors who do not always pay great attention to harvesting only under ideal conditions. The crop is often harvested late in the autumn when the soil is wet. The machinery leaves deep wheel ruts which become drainage channels within the fields, leading to rill or gully erosion;

- The crop is seen as, or often grown because it can be used as, a dumping ground for slurry - with the associated problems especially those associated with travelling on the land during the winter months;
- Because the land area is bare overwinter, there are major opportunities for runoff (and erosion) to occur;
- The lack of vegetation, as well as exacerbating runoff, makes maize stubbles a hostile environment for most creatures/wildlife and native plants.

There is much that can be done, and easily, to counter the runoff problems. The techniques that can be used have other on-farm benefits, and benefits for the environment, including wildlife. Further comment on this is made in Section 4.

The only measurements of runoff that have been made in maize under a range of management strategies in the UK appear to be those made by Clements and Donaldson (2002) and Clements *et al.* (unpublished). They carried out small-plot experiments on maize (*Zea mays* L.) at IGER North Wyke (Devon), IACR Long Ashton (near Bristol) and an on-farm site in North Devon. Plots were hydrologically isolated at the soil surface, and the volume of surface water draining from them measured via a tipping bucket system. Four treatments were investigated (conventional maize bare stubble, chisel ploughed stubble, Italian ryegrass understorey and ryecorn winter cover crop). During the winter of 1999-00 the winter cover crop (ryecorn) reduced water runoff marginally during the measurement period to 381 m^3 ha^{-1} (total for eight rainfall events) compared to 433 m^3 ha^{-1} from the conventional bare stubble plots. The Italian ryegrass understorey reduced runoff to 160 m^3 ha^{-1}, but chisel-ploughing reduced runoff to only 10 m^3 ha^{-1}.

Similar experiments were carried out at North Wyke during the winter of 2000/01 and at a site on a different soil-type in North Devon (Frithelstock). Chisel-ploughing reduced water runoff at both sites, but sowing a winter cover crop markedly increased water runoff at both sites.

At Long Ashton in 1998/99, the impact of (a) ploughing v. non-inversion tillage, (b) conventional maize row width (75 cm) v. narrow rows (12.5 cm) and (c) drilling across the slope v. drilling up and down the slope were compared. Drilling across the slope reduced water runoff by 40%. In later work a combination of white clover understorey plus drilling across the slope reduced water runoff by nearly 90%, but the clover understorey reduced the yield of maize. Drilling across the slope even with no clover understorey (and hence no impact on yield), reduced runoff from 223 to 49 m^3 ha^{-1} during the measurement period in 2000/01.

Although usually beneficial in the work, the magnitude of the impact of chisel ploughing varied between sites and years. The authors thought this likely to be related to soil type and moisture status.

Following their study of an exceptional rainfall event in south central England in may 1993, Boardman *et al.* (1996) were firmly of the view that the risk of erosion and off-site damage will be greater if the area planted to maize (or linseed) increases in the future.

Boardman *et al.* (1994) reckoned that flooding by soil-laden water has become more common in the last 20 years in parts of the UK (and elsewhere in Europe). They said that winter flooding was often associated with wet soils and the cultivation of winter cereals and summer flooding with thunderstorm activity in sugarbeet, maize and potatoes. They commented that policy response has generally been limited.

Ruttimann *et al.* (1995) pointed out that considerable variation in runoff and soil loss can occur within apparently homogenous fields of maize. Goeck and Geisler (1989) studied the impact of white clover as an understorey, to reduce runoff and erosion, on the yield of maize in Germany. Yield losses could be substantial, as found by Clements, R.O. (unpublished) in the UK, however if the clover was sown when maize plants were 15 or 30 cm high, no yield loss was recorded.

Kwaad and Mulligen (1991) found that runoff coefficients were 41.7% for a conventional maize system, 14.9% for an autumn and spring tilled system and 47% for a direct drilled system following a high intensity rainfall event.

Diez and Kainz (1986) warned in their work in Bavaria that slit planting of maize could greatly reduce yields, but runoff (and soil loss) was greatly reduced. When undersown at the same time as maize even weakly competitive species such as *T. subterranean* and *T. dubium* could reduce yield substantially (Schafer, 1986). Overwintering catch crops sown after maize harvest and with therefore no effect on yield (Italian ryegrass or winter rape) reduced runoff to 12% of that from bare fallow.

Bare soil, conventional tillage and traditional tillage had higher runoff (and sediment yields) than treatments with no tillage in work in Mexico (Tapia-Vargas *et al.*, 2000).

Rhoton *et al.* (2002) reckoned that no-till practices generally reduce runoff in the USA, largely because they result in greater organic matter control of the surface layers of the soil, with the consequent benefits to structure. In their work using rainfall simulation, bulk density, as a single variable, explained much of the variability in runoff from no-till treatment. Runoff decreased due to the development of greater porosity in the surface soil layers. However Tan *et al.* (2002) found that runoff from mould board ploughed areas was less than for minimum tillage maize during the non-cropping period, although this was not the case for all farms, sites or years.

Also in the USA, Meyer *et al.* (1999) found that most conservation systems reduced runoff by at least 10%. No-till with a vetch cover crop generally reduced runoff most. Meyer *et al.* (1997) also commented that the greatest reduction occurred during years of higher runoff amounts. Some 92% of erosion occurred during the maize years of a four year/wheat/meadow/meadow rotation (Shipitalo and Edwards, 1998). Hall *et al.* (1984) found that “living mulches” e.g. birdsfoot trefoil (*Lotus corniculatus*) and crown vetch (*Coronilla varia*) reduced runoff.

Intercropping significantly reduced runoff compared to maize grown alone in Kenya (Kariaga, 1999). Bekele and Thomas (1992) also working with maize in Kenya reported that surface cover reduced runoff (and soil loss) and that infiltration rates were generally increased. In South Africa, Russell (1991) found that runoff was considerably lower in plots of maize when no-till was practised, leaving crop residues on the surface, compared with other methods.

In Italy, Acutis *et al.* (1994) also concluded that runoff from cereal crops and maize was far greater than from perennial crops. Plant cover was the main means by which erosion (and runoff) could be reduced and for maize a maize/ryegrass intercropping system seemed to work well.

Sedimentation can clog navigation and water conveyance systems such as roadside ditches and reduce reservoir capacity and damage recreation sites (Uri, 1999).

Effect of forage crops on runoff

Overgrazing of kale by sheep compacted the soil surface to the extent that the infiltration capacity was in the order of 0.1 mm/hr (Heathwaite and Burt, 1992).

In the USA, Zemenchik *et al.* (1996) tested the hypothesis that smooth bromegrass (*Bromus inermis*) grown in mixture with lucerne (*Medicago sativa*) would reduce runoff and soil loss which can occur due to surface sealing of lucerne, but no reductions were found to occur.

Dixon *et al.* (1983) found a trend for a lucerne/fescue mixture to retain pollutants better than the other sward mixtures they tested, but runoff volume was not greatly affected.

Effect of poultry/chickens on runoff

The only relevant references found were from work in the USA. Chickens or other poultry are seldom kept commercially on grassland, but their waste products may be applied to swards. There appears to be no evidence from the literature relating to the few instances where the birds are kept on grassland or where their waste products are applied that there are any effects on the hydrology of the area. Edwards and Daniels (1994) for example, in work with simulated rainfall, found no effect on the hydrological characteristics of receiving grass plots of the applications of poultry litter or poultry manure (or pig manure). There were impacts however on the nutrient content of the runoff in terms of N and total P. The application of broiler litter did not significantly affect hydrological properties of the soil in their earlier work either (Edwards and Daniels, 1992).

The application of organic wastes (dairy manure, poultry manure, municipal sludge) had effects on the level of nutrients in surface runoff, but did not affect the volume of water runoff (McLeod and Hegg, 1984). Westerman and Overcash (1981) found that the timing of waste application in relation to rainfall events can be very important in reducing runoff pollution. There was no evidence that application of waste products affects the volume of surface water runoff.

Effect of agricultural drainage on runoff

Effective drainage in restricted permeability soil problems will almost certainly demand the presence of permeable backfill and a commitment to maintaining secondary treatments of subsoiling or moling. Against this background the debate as to whether or not agricultural drainage has increased or decreased flooding downstream has continued for decades. There have been many reviews and discussion papers on this subject matter (Kendell, 1950; Trafford, 1973; Weyman, 1975; Bailey and Bree, 1980; Rycroft, 1990, Ward and Robinson, 1990).

Rainfall varies in terms of intensity, depth and frequency. Antecedent conditions at a site (vegetation, roughness, compactness) influence contributions to the drainage systems. Infiltration controls the amount of water entering the soil. Rainfall in excess of the infiltration capacity will generate runoff. Storage on the surface will modify runoff hydrographs. The soil characteristics (both natural and modified by tillage) influence the rate of water movement to subsurface drains.

Some soils contain significant macropores (e.g. clays) that permit rapid bypass routes for soil water to depth or to subsurface drainage systems. The characteristics of subsurface drainage systems and their continued maintenance will affect to rate at which the soil water reaches arterial drainage networks.

Each field or sub-area will have its own set of environmental characteristics (e.g. soil-type, climate, topography, vegetation cover, artificial drainage, soil management regime etc.) which will govern the generation of runoff under certain conditions. The transfer of this water to the catchment outlet is dependent on the connectivity of the field/sub-area to the main arterial watercourse, the slope of the watercourse, the hydraulic roughness of the watercourse (e.g. in-channel vegetation and sediment) and the straightness of the watercourse. Differences in time of travel for water from individual fields or sub-areas to reach the point of interest will affect the magnitude of the flood peak. The relative importance of field drainage and main channels varies with storm size - field drainage tending to dominate for small-medium storms, but channel improvements dominate for large events. This finding was also reported by Bailey and Bree (1980).

Soil factors affecting drainage. These include:

- Soil-type
- Drainage type
- Drainage intensity
- Soil water storage

- Rainfall characteristics
- Topography

Field experiments have shown the effects of drainage on flows are dependant on site characteristics controlling the natural soil water regime, especially soil permeability and rainfall (Ungar and McCalla, 1980; Armstrong, 1983; Robinson *et al.*, 1985; Robinson *et al.*, 1987; Arrowsmith *et al.*, 1989). Outflows from fields are routed through a channel network (with is own maintenance regime) to point of interest in the catchment. Arterial channel improvements (e.g. reshaping, enlarging, vegetation removal and straightening) increase the channel capacity, decrease the channel length and therefore increase the channel gradient. An increased channel capacity reduced the incidence of bank overtopping but peak flows at all locations along the channel are increased (Linsley *et al.*, 1988).

The magnitude, and even the direction, of the change in flows due to drainage can differ between the field and catchment-scales due to:

- **Dilution effect.** Not all farmland is drained, due to physical factors (inc. soils, topography) and social factors (return on investment and land tenure);
- **Distribution effect.** Location of drainage works affects the hydrological response in the catchment. The travel times from different parts of a catchment will vary and this will affect the peak catchment flow;
- **Deterioration of drainage effect.** A new drainage scheme is most effective when it is first installed and then declines over time. This is particularly true for soils needing regular subsoiling or moling;
- **Channel routing effect.** Stream channel improvements (e.g. dredging, vegetation removal, straightening) shortens travel times and reduces within catchment storage and attenuation.

Catchment studies generally do not have good information in the amount, location and timing of drainage works. The Ray and Catchwater catchments (Robinson, 1990) indicate that river channel improvements, rather than field drainage, had a much greater contribution to high flows. Robinson concluded that general statements on whether drainage “causes” or “reduces” flood risk downstream are oversimplifications of the complex processes involved.

Field-scale effects. In-field underdrainage can increase or decrease peak runoff (Armstrong and Harris, 1996, Robinson and Rycroft, 1999). Surface drainage increases peak flows by reducing surface storage. The effect of subsurface drainage depends on site wetness. High watertable fields (due to high rainfall or low permeability) creates surface or near surface flow. Drainage increases soil water storage capacity, increases infiltration and reduces surface runoff and peak flows. Low watertable fields (due to low rainfall or high permeability) produces flow through main soil profile. Drainage in this case increases peak flows due to shorter flow paths and steeper hydraulic gradients.

Main channel effects. Cleaning, straightening and deepening cause peak flows to increase due to a reduction in overbank storage and faster travel times (Robinson & Rycroft, 1999).

Catchment-scale effects. Synchronicity of flows from different sub-catchments will affect peak flow at the point of interest. The relative importance of field drainage and main channels varies with storm size - field drainage tends to dominate for small-medium storms, but channel improvements dominate for large events. Overall, drainage schemes with substantial surface drainage and main channel improvements will lead to higher peak flows downstream.

Under different circumstances of ground wetness, subsurface drainage may increase or decrease peak flows. If rainfall exceeds infiltration capacity then any surface drainage improvements will be important. While surface and main channel drainage will reduce the time of travel, the overall impact downstream depends on relative importance of field and main drain flows. This depends on the total catchment area and the magnitude of the flood event and on the relative timing of storm flows from the sub-catchments.

Drainage status. The lower drainage status on many clay soils suggested by Harris & Pepper (1999) is important because this will affect many clay-based soils, where intensive drainage has historically been backed by a good secondary drainage system. Table 3.5 and Figure 3.1 show the dramatic fall off in area benefiting from new drainage schemes installed with grant aid in the period 1981-85 (Harris, 2003) compounded by the installation of little new drainage after the removal of all grant aid in 1985 (Harris & Pepper, 1999).

	1971 to 1975		1976 to 1980		1981 to 1985		
Division	**Records**	**Benefit Area (ha)**	**Records**	**Benefit Area (ha)**	**Records**	**Benefit Area (ha)**	**Total Benefit Area (ha)**
Alnwick	1,474	11,666	1,070	10,951	221	2,123	**24,740**
Beverley	3,107	22,625	2,718	26,549	729	7,840	**57,013**
Bury St. Edmunds	4,088	29,828	3,153	26,660	362	2,911	**59,398**
Caernarvan	1,185	4,779	1,210	4,591	307	927	**10,296**
Cardiff	562	2,388	459	2,281	190	809	**5,477**
Carlisle	1,612	8,237	1,541	7,421	412	1,533	**17,191**
Carmarthen	3,048	10,518	2,373	8,745	1,663	5,139	**24,401**
Chelmsford	6,615	51,355	3,483	33,555	53	524	**85,434**
Crewe	3,281	13,826	2,253	10,587	292	1,476	**25,889**
Durham	497	3,203	475	3,014	184	848	**7,065**
Exeter	2,495	9,543	2,221	8,695	917	3,969	**22,207**
Gloucester	1,915	11,307	1,415	11,351	750	6,187	**28,845**
Guildford	1,180	10,524	989	7,945	119	1,193	**19,661**
Harrogate	2,739	18,008	2,242	15,036	249	2,213	**35,256**
Huntingdon and March	3,745	43,225	2,757	30,908	1,288	14,641	**88,774**
Lincoln	9,875	86,586	6,669	59,586	972	11,329	**157,501**
Llandrindod Wells	3,018	10,056	2,153	7,487	734	2,398	**19,941**
Maidstone	1,518	13,463	899	7,669	174	1,395	**22,526**
Northallerton	2,015	16,067	1,856	14,386	236	1,662	**32,115**
Northampton	3,450	26,762	2,834	24,471	540	5,252	**56,484**
Norwich	2,997	30,462	1,967	19,593	71	720	**50,774**
Nottingham	1,550	9,886	1,068	7,864	535	3,452	**21,202**
Oxford	2,278	23,468	1,889	19,450	594	6,790	**49,708**
Preston	1,790	10,231	1,373	7,084	84	556	**17,871**
Ruthin	1,080	3,646	983	3,819	522	1,688	**9,153**
Shrewsbury	2,270	10,627	2,081	9,847	1,139	5,130	**25,604**
Taunton	2,381	9,804	1,979	9,310	512	2,871	**21,985**
Truro	822	3,200	806	3,415	158	472	**7,087**
Winchester	554	2,899	609	3,999	93	520	**7,418**
Worcester	4,021	22,868	3,291	20,432	1,215	9,497	**52,797**
Totals:	**77,162**	**531,052**	**58,816**	**426,698**	**15,315**	**106,061**	**1,063,811**

Table 3.5 Number and benefit area of grant application records in the CG3UD database, by MAFF (pre 1974) drainage division (CG3UD, 1971-85).

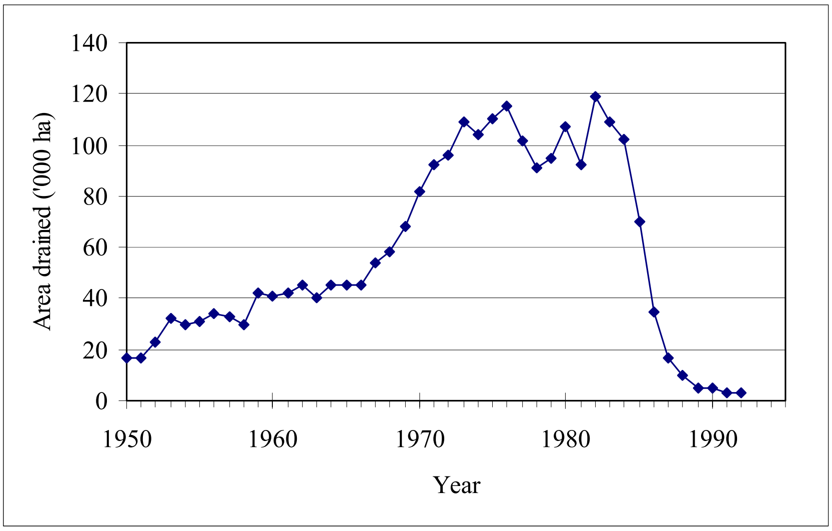

Figure 3.1 Area of land drained each year in England and Wales.

Moorland/peatland drainage. A high watertable is essential in peatlands. Peat forms under waterlogged conditions and decomposes when exposed to air (Rowell, 1988; Heathwaite and Gottlich, 1993). Peat systems lose water via runoff, sub-surface flow or evapotranspiration and gain water through rainfall, inflow from bordering areas or ground sources.

Runoff can be enhanced by cutting and maintaining ditches in the peat surface. Sub-surface flow can be enhanced by cutting into mire margins or drying the surface layers. Evapotranspiration may increase as vegetation changes, especially if woodland encroaches following a sustained drying out period.

The influence of ditching on upland peat or mineral soils has been investigated by Robinson (1990). Most studies conducted focused on the influence on peak flows and showed an increase following pipe or ditch drainage (Robinson, 1988; Schuch, 1976). Research at some sites has however, suggested a reduction in peak flows (Burke, 1975; Baden and Egglesmann, 1964; Acreman, 1985) found that flood peaks were dependent on both the spatial and temporal distribution of land use. Ploughing and planting of a small drainage basin in the Southern uplands resulted in flood peaks when the activity was in the lower part of the basin whilst a similar practice in the upstream section was followed by a substantial increase in peak flows.

Artificial drainage can lower the watertable in the peat, change the pattern of water retention and movement in the peat body, change the magnitude and spatial distribution of runoff and increase the incidence of flooding (Backshall *et al.*, 2001). The overall water storage capacity (“sponge effect”) of the peat body is significantly reduced and excess water is passed quickly downstream.

Moorland drainage used to be subsidised in the UK and widely practised, to improve the vegetation for grazing stock and for grouse shooting interests. Grants are no longer available and it is discouraged, so it has declined. However, without active intervention for restoration purposes the consequences of historical moorland drainage will remain for centuries.

Hedges as landscape features. In the UK hedgerows are viewed as having significant ecological and cultural value. Their importance to impeding surface runoff and flood generation has been discussed earlier. Robinson and Sutherland (2002) reported that there has been a 50% reduction in Britains hedgerow stock since 1945. The Countryside Survey in 1990 also revealed a drastic reduction in the length of hedgerows in Britain between 1984 and 1990 of 23% (Barr and Gillespie, 1999). However, the following survey in 2000 showed that hedgerow restoration and planting now compensated for any neglect and removal, such that between 1990 and 1998 the decline in hedgerow length was halted (Petit *et al.*, 2001).

Numerous open ditches have been lost from the arable landscape during the 1960's-1980's agricultural intensification period. During this time various grants were made available to farmers to improve their land drainage and potential economic return from their land. The large linear reservoirs that the open ditches provided were either lost permanently or converted into much smaller underground pipe or culvert systems designed to transport water very quickly.

4. Mitigation measures and practices

Flood mitigation measures and practices are reviewed here, based largely on the reviews in Sections 2 and 3.

4.1 Grassland

It seems clear from the literature that changes in livestock husbandry practice during the last few decades has led to a greatly increased likelihood of flooding. The major causes have been increased stocking rates and the drive to increase the length of the grazing season, leading to a greater degree of treading, surface sealing and then runoff, leading to flooding.

However, much can be easily done to reduce the risks. It is important to remember that changes in livestock husbandry or grassland management aimed at reducing water runoff have other on-farm benefits as well as benefits to the wider environment generally.

The main driver to increase stocking densities have been economic ones e.g. headage payments. However, EU reforms leading to area payments instead will reduce considerably the pressure to retain high stocking levels. Reduction in the number of livestock units kept per hectare will reduce treading and, probably, runoff and flooding.

4.2 Maize

Kwaad and Mulligen (1991) found that soil loss from a direct drilled maize crop during a high intensity rainfall event was only 15.6% of that from a conventional system. They ascribed this to low detachment rates of soil material by drop impact and overland flow due to the presence of winter rye remains. This indicates how runoff reduction measures could be developed.

Barkusky (1990) working on loamy sands at Meuncheberg found that soil loss (and therefore probably runoff) was reduced by planting winter rye, oil radish, spring or winter rape or cocksfoot between rows of maize. Yield was however reduced. Cover crops may also reduce weeds (Zink and Hurle, 1989; Zink and Hurle, 1990). Diez and Kainz (1986) also found runoff and erosion to be greatly reduced by the use of cover crops. Their work also investigated the impact of sowing barley in wheel tracks, but results were variable. In Schafer's (1986) work, winter cover crops reduced runoff by 88% compared with a bare fallow. Hartwig (1985) summarises a good deal of work relating to the use of crown vetch (*Coronille varia*) in the USA as a living mulch in maize.

Goeck and Geisler (1989) investigated the consequences of sowing date of a white clover understorey with maize on surface runoff. The clover greatly reduced runoff and had no effect on yield if sown when the maize was 15-30 cm high.

Cruse *et al*. (1995) advocated strip intercropping as a means of reducing surface and sediment runoff. They experimented with 15ft (4.6 m) wide strips of maize, soya and oats/berseem clover (*Trifolium alexandrinum*). There were yield advantages as well as a reduced need for N fertiliser in maize following clover/oats in addition to the reduction achieved in surface water runoff.

Dabney *et al.* (2001) reviewed the use of winter cover crops to improve soil and water quality. Their review mostly relates to arable cropping situations, but the principles would be relevant to a number of forage crops grown in the UK, including maize, whole-crop cereals and forage lupins. In general terms, they wrote, cover crops reduce sediment production (and runoff) from crop land by intercepting the kinetic energy of rainfall and by reducing the amount and velocity of runoff. There are also beneficial effects on soil quality and biological parameters. The following extract is taken from their review:

"The fact that only a very small percentage (of US cropland) is currently planted with cover crops suggests that most producers find the disadvantages more evident than the advantages. While cover crops may increase water infiltration into soil and soil water holding capacity, they also use water to grow and can potentially reduce yields of the subsequent crop. This is less of a problem in humid areas."

Melville and Morgan (2001) investigated the use of contour grass strips to control erosion in a field in Bedfordshire. They used two common pasture grass species, *Festuca ovina* and *Poa pratensis* which have different growth characteristics in terms of height, tiller density and leaf size. Strips of both grass species resulted in significantly reduced runoff and soil erosion compared to bare soil. However despite the substantial differences in structure of the grass plants with the strips, there were no differences between them in terms of reduction of runoff or erosion control. The effect of the grass strips was to cause ponding up-slope which led to particulate deposition in the areas above the barrier. In runoff plots in Shropshire, Auersweld (1998) found that erosion rates were decreased considerably by leys, which were effective for soil conservation even on steep slopes. He suggested that grassland could be used as a 'soakaway' in an arable system - braking, filtering and infiltrating runoff.

Planting tussock grassland in New Zealand with radiata pine (*Pinus radiate*) reduced runoff considerably, especially during drier periods (Fahey *et al.*, 1998).

Kwaad *et al.* (1998) were convinced that in the last 30 years erosion, with the associated flooding, had increased significantly in the Netherlands. Conservation cropping in maize however, although while reducing soil erosion, did not reduce runoff as much as a surface mulch. Brandt and Wildhagen (1996) found that the application of shredded material greatly increased water infiltration and reduced surface runoff. In the Netherlands, Geelen *et al.* (1995) advocated the use of a straw mulch, which greatly reduced soil loss (and runoff) without affecting yield.

Bazzoffi *et al.* (1995) suggested that urban refuse compost could be used to help improve soils. A mulch made from composted urban waste or green waste could be applied to maize to reduce runoff and later, when ploughed in, it would improve the soil organic matter content. Bazzoffi *et al.* also reckoned that low pressure (i.e. wider) tractor tyres may help reduce the risk of creating runoff channels in maize.

Geelen *et al.* (1995) found that soil tillage in autumn reduced runoff (and soil erosion) from maize, but use of winter rye as a cover crop had no effect. Straw mulch reduced runoff without affecting yield.

Kwaad et al. (1998) concluded that a surface mulch of straw was an effective measure in reducing runoff. Wurfel (2000) recommended the use of a mulch to reduce erosion/runoff. Brandt and Wildhagen (1996) recommend the use of shredded greenery perhaps in contour strips or headlands. Ruttimann and Prasuhn (1993) recorded a reduction in runoff where a much had been used in Switzerland, as did Schmidtlein (1991) in Germany.

Bayon and Binet (2001) found that earthworm activity affected runoff in maize. Earthworm casts were especially erodable, but acted as a brake on soil erosion by creating surface roughness. Also, the burrows left by some species greatly aid water percolation and hence reduce runoff.

Subsoiling post drilling between rows of maize reduced runoff in Jasa and Dickey's (1991) work in Nebraska. Neururer (1984) found that a bituminous emulsion could be used to reduce runoff from maize.

Sowing maize in twin row configurations reduced runoff (Sojka *et al.,* 1992) in work done in Idaho and may be worth exploring here, although Donaldson, G. (unpublished) has done some work in this area and found little effect on different maize planting arrangements.

Ammon and his colleagues working in Switzerland carried out several experiments investigating the use of mulches, living mulches and understories to prevent erosion and runoff in maize (Ammon *et al.*, 1995; Ammon, 1994; Ammon *et al.,* 1990). This culminated in the development of a special machine that slot-seeds maize into band-sprayed areas of pasture. The machine is slow and cumbersome, but has proven so successful in reducing the amount of herbicide needed and preventing runoff and erosion that it is now used widely in Switzerland and some other parts of Europe. Trials in the UK are taking place (C. Moore, *Pers comm*.).

Anonymous (1992) refer to the same or a similar machine for direct drilling in grassland which is mounted on a rotary tiller and also mulches weeds between seed rows. Runoff was reduced by a red clover understorey in maize in work by Wall *et al.* (1991) in Canada and could be achieved with no loss in yield.

4.3 Managing infiltration to control runoff

A number of management techniques exist for managing infiltration and thereby reducing runoff which include the management of surface cover, improvements to the structural conditions of the soil and the construction of runoff retardation structures.

Surface crop cover

Vegetation/cropping. Crops with a dense canopy, such as grass, will have the effect of reducing the kinetic energy of the rain on the soil surface. This energy can cause particle detachment. The greater the energy, the greater the number of smaller particles that are moved. Small particles are harder to detach than larger ones, but are easier to transport. Therefore, movement of the soil particles through raindrop impact and detachment often results in surface capping. By covering the surface, and thereby protecting the soil from direct raindrop impact, detachment is prevented thus soil structure can be retained.

Vegetation can reduce erosion by decreasing runoff velocities, by physically restraining soil particles, increasing organic matter in the soil profile, intercepting rainfall, and by opening pathways into the soil, see Holtan & Kirkpatrick (1950). From the estimation of runoff calculations and N and C coefficients required for the prediction of runoff, it is evident that bare soil and row crops are extremely poor at reducing runoff and erosion especially where the crop rows run up and down the field slope. The impact of tillage operations used to prepare a smooth, level seedbed in order that faster and more accurate sowing techniques can be adopted are deleterious to soil and water conservation. Utilising a cover crop, under sowing one crop with another to protect the soil surface, or employing a reduced or minimal tillage regime, will reduce the problem. Careful selection of crop rotations can enhance this by ensuring that soils that are particularly at risk are under an extensive canopy (be it a surface mulch or crop cover) at the more critical times of the year. Incorporation of set-aside (as buffers) should also be considered as the vegetation cover should reduce the runoff.

The protective canopy afforded by tree cover on the soil often gives complete protection. This is not due to the canopy reducing the rainfall energy, because under a canopy of 10-metre height, the opposite is often true, but because of the accumulated leaf litter on the soil surface that acts as surface mulch. Raindrop kinetic energy is often greater under tree cover, because the small, natural raindrops accumulate on the leaves and branches, before morphing into one large drop that releases when its mass exceeds its surface tension. Falling from a height of 10 metres the droplet has enough time to reach terminal velocity, thus its erosivity potential is far higher (Hudson, 1995). In UK woodlands, due to the slow oxidation and decomposition rates of vegetative matter compared to the tropics, a build up of leaf litter and often a dense under storey of vegetation results, which is useful in dissipating the raindrop energy in order to reduce the overall impact. Data from the SCS (1972) gives the lowest value of runoff curve number for these conditions.

The results of a study of the effects of deforestation of 94 catchments by Bosch and Howlett (1982) demonstrated that there was a consistent pattern of increased annual flow. Houghton Carr (1999) reports that with reforestation initially the improvement of the site by drainage increases peak flow with lag times about one fifth to one third shorter and the peaks are 20% to 40% higher than the pre-drainage status. In the 10 years following tree planting the response times and peak and bore flows regress to the former values. Houghton Carr (1999) reports that in the UK the main research sites are at Plynlimon in mid-Wales, Balquhidder in the Central Scottish Highlands and Coalburn in Northern England. The results of these are included in numerous reports by the C E H Wallingford. It must be noted however that all the forestry research sites listed are in high rainfall areas with shallow soils or peat over impermeable substrates.

Crop cover can be used to bind the soil surface together and to increase inception time and therefore infiltration. Some root crops, when grown in rows, can produce similar results to a bare crusted surface, especially at certain wetter times of the year. The use of rows and the associated wheelings can form the perfect gully for runoff to use.

Armstrong *et al*. (1990) produced Table 4-1, indicating the relative erosiveness of the different land features.

Least Risk	Forestry / Woodland
	Permanent Pasture
	Spring Cereals
	Autumn Cereals
	Short Term Grass Ley
Greatest Risk	Sugarbeet / Potatoes / Horticultural Crops

Table 4.1 Relative erosion / runoff risk

New crops required for energy and biomass such as Miscanthus and Short Rotation Coppice (SRC) can afford a significant amount of protection. Miscanthus when established is harvested annually but not until the cell moisture has dried to 15%, which is usually early spring, when the leaf material has fallen to the soil surface. The life for a Miscanthus crop is anticipated to be 15 years (Loxton, 2003). Observations of the soil conditions under the canopy litter of a Miscanthus stand that had been established for three years showed an open porous surface, which was in direct contrast to adjacent bare field conditions. This crop therefore has the potential to maintain infiltration rates for an extended period. SRC has a similar surface mulching effect. Although the establishment period can range from 3 - 5 years, the long harvesting cycle of 3 - 5 years (DEFRA, 2002) should result in a significant build up of surface mulch.

Stock control. Heathwaite *et al.* (1990) found that there is a possible 80% reduction in infiltration capacity on grazed land if stock were allowed to trample and compact the soil surface. They concluded that *"runoff from heavily grazed* *permanent grassland is at least double that from lightly grazed areas, and nearly twelve times greater than that of ungrazed (temporary grassland) areas".*

Reducing this problem will allow an increase in surface infiltration, and improved soil structural condition. Mini moling, if the soil is in a plastic condition, will aid the percolation of water from the topsoil through to the sub soil. If the problem is purely one of surface crusting or compaction, this can be alleviated through the use of a slot cutting or spiking machine. The main issue is that the stock will soon destroy the surface, especially sheep.

To solve this problem a two-fold approach is needed where the aims are to:

- increase the strength of the soil by increasing the depth of the watertable if one is present;
- manage the land area to have zones for the stock where compaction is caused and the infiltration rate is effectively zero, above an area which is less compact and where infiltration can take place.

The relationship between watertable depth and soil bearing strength is illustrated in Figure 4.1 from the work of Massey *et al*. (1974), which shows that as the watertable is lowered the soil strength, reflected by the penetration resistance, increases in a linear manner. They concluded that to prevent poaching the watertable must be kept at 0.5 m below the soil surface, which increases the soil strength by a factor of two and gives a penetration resistance of 350 kPa. It is estimated that for a sheep with a body mass of 40 kg and area per foot of 0.0006 m^2, the pressure under the sheep's foot, when static, is approximately 160 kPa. This could easily rise to 320 kPa when walking and to 480 kPa under dynamic conditions (Blackburn, 2003).

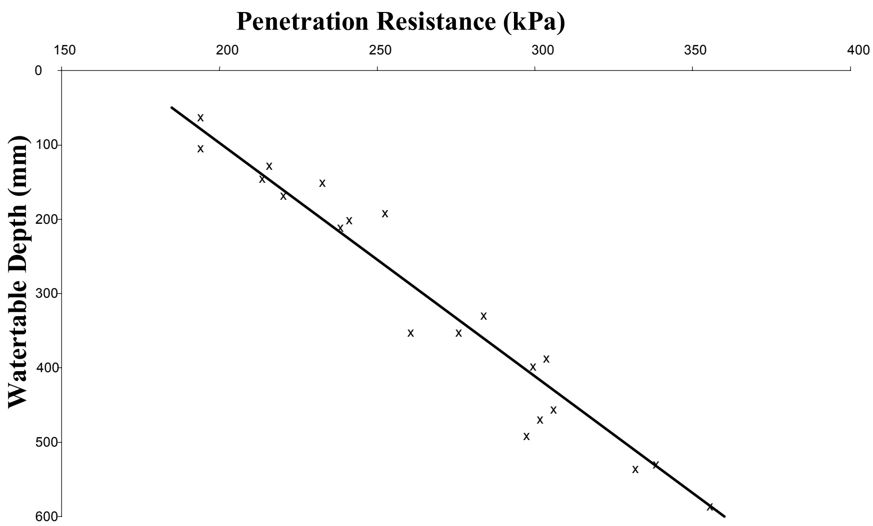

Figure 4.1 The relationship between watertable levels and the surface strength of grassland (redrawn from Massey et al., 1974)

At Pont Bren, an approach to manage stock gas been developed by Welsh farmers at Pontbren, (Baines, 2003), with interesting hydrological implications. There, a group of 10 farmers found that sacrificing some of their least productive areas, to copses and non grazed areas, provides an ideal opportunity for the up slope runoff to infiltrate, as the infiltration rates in the copses and the non-grazed areas of the farms have recovered. This in turn has had a modulating effect on the rise and fall of the streams and ditches on the farms.

Soil management conditions

Castle *et al*. (1984) reported that compaction of the surface soil layer by cultivation practices, heavy machinery or livestock, will greatly reduce the infiltration rate of even the lightest soils. The use of 'tram lines' in an attempt to concentrate the effect of heavy machinery has met with much success.

They also reported that direction of ploughing, subsequent cultivations, the planting of row crops and potato ridging on sloping fields also affects runoff, which is aggravated with the use of wide implements where the practice is to travel up and down the slope. This has the effect of creating ready-made rills or channels for water to concentrate into and rapidly move down slope with increasing quantity and velocity. When these operations are carried out across the slope, water is held back, or its movement greatly slowed by the crop rows, thereby increasing the time of opportunity for infiltration or evaporation by the creation of surface storage conditions. Recent studies in Somerset and Devon on the effect of this on the cultivation practices have been undertaken by Clements and Donaldson (2001). These results showed a profound reduction in runoff for non erosive soil conditions. However chisel ploughing did cause more erosion on the lighter soils at IACR, Long Ashton.

Soil loosening and mole drainage. Deep ploughing, chiselling, ripping and other forms of subsoiling have long been used in agriculture to remove compacted layers that inhibit the development of plant roots and restrict the free flow of water and air through the soil profile. The general objectives are to produce better continuity of pores from the surface to depth, break through any subsurface compaction layers, and to create fissures that will allow better infiltration of water.

Equipment to perform such operations is readily available using many of the principles developed by Spoor and Godwin (1978) to improve the effectiveness of soil loosening. A simple yet effective example of this is the concept of the "in furrow" loosener which is attached to the headstock of the mouldboard plough immediately behind the "in furrow" tractor wheel. This will remove the "plough pan" compaction referred to by Hawkins and Brown (1963) and Davies *et al*. (1973).

Studies on the design of the mole drain plough by Godwin *et al*. (1981), showed the presence of well formed vertical cracks alongside the leg crack with strong supportive soil blocks. This condition may be more important for soil water management than general soil loosening alone. This work provides a rigorous understanding of the fundamentals of soil disturbance with very narrow tines (Godwin and Spoor, 1977), from which it is possible to design implements to obtain both soil loosening and slot and channel formation. An example of which is the mini mole, i.e. a mole plough with a smaller diameter foot to produce cavities at shallower depths than the “classic” mole drainer.

Leeds-Harrison *et al*. (1982) reported the results of studies into the pathways by which water flows into mole drains, and showed the importance of these fissures and cracks for infiltration. The drain outflow recorded for a soil with leg cracks and fissures on a 20 m^2 “plot” catchment, was three times that of a soil without leg cracks and the associated fissuring. The hydrographs from these studies are shown in Figure 4.2.

As these soils were not saturated, and there was no runoff evident, it can be assumed that a well structured, fissured and cracked clay soil will have at least a three fold infiltration rate increase compared to that of a similar soil with no man made fissures or cracks. The authors concluded by stating that large cracks have a significant influence on the hydrologic characteristics. These cracks fill and empty at very low tensions, and provide rapid water removal from the upper soil layers. If no cracks exist the effectiveness of the drainage system is solely dependent on the natural hydraulic conductivity of the undisturbed soil and if the infiltration rate is less than the rainfall rate then runoff will occur.

It can be seen from Figure 4-2 that improved drainage, provided by the open leg slot, can cause the peak of the hydrograph to be increased with a shorter time to peak which could, if not managed correctly, have an adverse effect on peak flow in the catchment. The key is to control the release of this water into lower sections of the catchment whilst the benefit of drainage is to help provide the needed buffer capacity to absorb rainfall and thereby reducing peak flows (Houghton Carr, 1999). It may not be practical on economic grounds to alleviate the reductions in drainage status, due to an overall deterioration in the UK drainage stock (Harris, 2003), however, in clayey soils, action should be undertaken to halt the decline in drainage status by encouraging farmers to maintain drainage outfalls and to check to ensure that there is an adequate connection between the surface soil and the sub-surface drainage system.

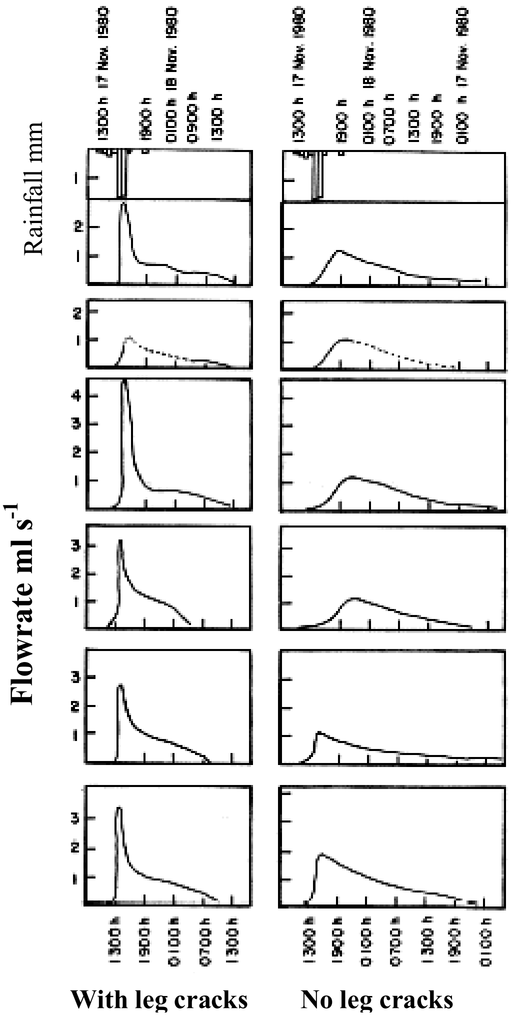

Figure 4.2 Drain discharge hydrographs (from Leeds-Harrison et al., 1982)

Where deeper tillage is concerned then care may be needed to ensure that there is no impact on archaeological factors. The use of Electrical Magnetic Induction (EMI) techniques as reported in Waine *et al*. (2000) and Godwin and Miller (2003) as a cost effective method (approximately £25 ha^{-1}) of determining both soil textural and structural variability and the presence of buried artefacts.

Wheelmark control. There is evidence to suggest that wheelings on the soil surface have a detrimental effect on soil structure. Young & Vorhees (1982) for studies in wheeled and non-wheeled areas show that after 100 minutes of rainfall the infiltration rate in the wheeled area is zero (i.e. 100% runoff). Reducing loads, decreasing tyre pressures and increasing tyre widths, to lower the pressure exerted on the soil, can only be beneficial to soil structure. The use of Terra tyres and tracked vehicles, especially on soils with an existing poor structure, can help to alleviate some of these problems (Davies *et al.,* 1973). In this case the peak vertical stress is 0.2 bar for the Terra tyre compared with 1.7 bar for a conventional tyre (Lebert and Burger, 1989). Delaying field operations until the soil condition is suitable to support the weight of large machines, or limit damage to surface zones, which can then be easily rectified during normal cultivation practices, is the best policy but becomes more difficult in a hard pressed agriculture where timeliness is everything. This is however very difficult with the commercial pressures at harvest time. The lack of available data pertaining to infiltration rates of soil trafficked with lower inflation pressure tyres indicates a need for further research.

Management techniques to benefit soil structure and increase infiltration can be adopted to remove the wheel marks. In doing so, surface roughness in the wheel track will increase, which slows runoff and increases infiltration. Increased roughness also results in increased localised depressional storage.

Thus, the chance of overland flow is reduced. If the wheel tracks are eradicated after an operation, careful placement can also keep runoff velocities low and reduce erosion. Care must be taken so as not to simply “rip up” wheel marks up and down the slope. This can create the perfect environment for the on set of gully erosion. In this case careful loosening and cross cultivation (Spoor, 2003), mole ploughing or “mini” mole ploughing are solutions to deflect the water into the surrounding soil.

Other options for reducing the downslope problems associated with tramlines could be tackled through other management options. On slopes where the runoff velocities will not be too great, the use of chisel ploughs to loosen the soil and therefore create localised surface depressions for increased detention and thus infiltration are well documented. Chisel ploughing to the correct depth will also assist in the eradication of surface capping and shallow subsurface compaction. With reference to frozen soils, work conducted in the USA by Pikul *et al*. (1992) to investigate the effects of tillage on frozen soils showed they have a much reduced infiltration rate compared to unfrozen or disturbed frozen soil. This was attributed to the cracks created by the chisel tune that provide water flow channels through the frozen layer.

As the gradient increases, then the use of mole ploughs and/or “mini” mole ploughs to assist in the transportation of the runoff away from the wheel marks into the loosened non-compacted zones either side is preferable. Chisel ploughing steep slopes often results in a more detrimental impact. The use of a corer or aerator, as described by Sheard (2000), for cutting cores from the wheel marked areas to increase the infiltration incidence, could be utilised. This would introduce pathways for the runoff to move vertically through the compacted and smeared surface zone. Slotting would create similar pathways, although the slot walls would tend to be more smeared that those of a corer, if created during periods of high moisture content.

On a similar theme, spiked wheels can be utilised to insert spike holes into the sides of the tramlines. This would have the effect of lifting the soil as the spike exits, creating fissures and cracks for water infiltration through the top surface. Other suitable devices could be constructed from the skimmers of mouldboard ploughs, or scalloped discs. The purpose of which would be to cut and tear the outer edge of the tramline and throw the compacted side portion of the wheel rut onto the inside of the rut. Removing the compaction from the side portion gives easy access to pathways for the runoff to infiltrate through the soil surface and into the subsoil and gives added stability for machinery carrying out further passes. Scalloped discs would be advantageous due to their leaving of a “rippled” finish. If aligned correctly to the direction of travel, this would cause variable surface profiles, thus potentially reducing runoff velocities and aiding runoff into the now accessible areas. Carrying out operations similar to those above needs to be thoroughly investigated before firm recommendations can be made, as there may be associated problems such as the stability of vehicles if the tramlines are removed.

Conventional practice is to install tramlines by shutting off drill coulters at the required spacings, depending on the system being utilised. Following sowing, there is usually no further operation on the ground until early November, when a herbicide is often applied. This operation will set out the tramlines for the rest of the growing season by driving in the empty rows left by the drill. Using lower pressure tyres for this operation, with inflation pressures between 5 to 10psi (0.3 to 0.7 bar) would result in reduced soil damage before the onset of winter and its associated rainfall.

Using Terra tyres to complete all other operations up until the end of March, when it would be standard practice to substitute them for row crop tyres, would aid with reducing possible soil problems. Godwin *et al*. (1997) operated Terra tyres on winter cereals and oilseed rape and concluded that the use of Terra tyres until April resulted in no damage that ultimately impaired the final crop yield. This could have the benefits of substantially maintaining higher infiltration rates as demonstrated by Davies *et al*. (1973), see Table 4.2. There are problems however, with the use of these tyres on narrow lanes and the intermediate inflation pressure tyres at 10 psi (0.7 bar) could be more appropriate.

It is important that all field-going machines have to adhere to this, namely combines, forage harvesters, root crop harvesters and trailers. Current sugarbeet and pea harvesters have a total weight approaching 40 tons, whilst not critical inn some catchments, this can have significant effects on soil conditions, and hence runoff, in other areas. This is especially true for the late autumn/winter harvest of sugarbeet. Agricultural contractors in Holland have resorted to active inflation-deflation tyre pressure control systems to help improve the trafficability of soils and the number of workdays (Spoor, 2003). Farmers can benefit from this as the contractor charges are kept competitive and there is less soil degradation. With the changing practices in agriculture, the contractor is a key player in improved soil management.

From these ideas, it is evident that further research is required with the purpose of developing the simplest, most effective method for handling the concentration of runoff in the tramlines.

Treatment	Infiltration rate (mm h^{-1})
Untreated land	820
Crawler TD6	79
MF135 (940 kg)	32
MF135 (2040 kg)	19

Table 4.2 Effects of compaction on infiltration rate (source: Davies et al., 1973)

Contour tillage and management. A simple, often advocated but seldom used, method of reducing the runoff through management techniques is to perform operations such as ploughing, planting, cultivating and harvesting approximately on the contour. This creates small depressions that temporarily impound the water and provide infiltration opportunities. Over a period of time however the effectiveness of contouring may decrease as surface sealing occurs. This is mentioned by Schwab *et al*. (1993) who state that *"runoff may be reduced by 75 - 80% initially and then may drop to 20% by year end"*. This is still a more favourable option than carrying out tillage operations up and down the slope, but takes significant encouragement for farmers to adopt these practices. The wheel marks and tramlines from this simple management change could act as surface interceptor drains. Loosening/cracking the lower face of the wheel mark, with either simple chisel or side inclined tines, permits infiltration into the soil.

The main difficulties with contour management are:

- Persuading farmers to change direction of operations;
- Operating on cross slopes on steeper gradients;
- Complex slopes where water has run along the contour and turned downslope causing significant runoff and erosion.

Care must be taken not to weaken the surrounding soil and produce longer-term stability problems.

Other practices. Strip cropping is a technique that reduces the overall slope length by interspersing strips of close growing crops with row crops. It has the advantage of always keeping some cover on the soil. When placed alongside streams (buffer zones) they act as temporary retention to runoff and as a sediment trap, unlike strip cropping they are non-rotational, but produce similar effects to strip cropping practices (Hudson, 1995; Morgan, 1995). It is critical therefore that buffer zones, if adopted, are significantly frequent and of suitable width to enable infiltration to take place and prevent the runoff from crossing the buffer zone.

A similar practice, but one that often requires extensive mechanical soil movement is terracing. Terracing effectively reduces the slope length and thus the velocity of the runoff. This in turn reduces the runoff's ability to transport large capacities of sediment. This practice is common in many parts of the world where soil erosion is a significant problem. Schwab *et al*. (1993), suggest that as terracing requires additional investment and causes some inconvenience to farming, it should only be considered only where other cropping and soil management practices, either singly or in combination, will not provide adequate erosion control or water management. With reference to Figure 4-3 it can be easily seen how treating a watershed with graded and open-end level terraces reduces the peak of the hydrograph (Allis, 1953).

Conservation tillage is an all encompassing term that refers to leaving previous residues on the soil surface, or only partially incorporating them, to reduce the overall exposure of bare soil to the elements, reduce surface sealing and increase infiltration, aggregation and provide resistance to wind and water movement. Often during a crop production cycle the timing of operations is dictated by factors not related to soil conservation (such as contract growing). In extreme circumstances this can lead to tillage operations taking place on soils that are in a relatively poor condition. Timing such as this destroys soil structure and greatly increases susceptibility to runoff.

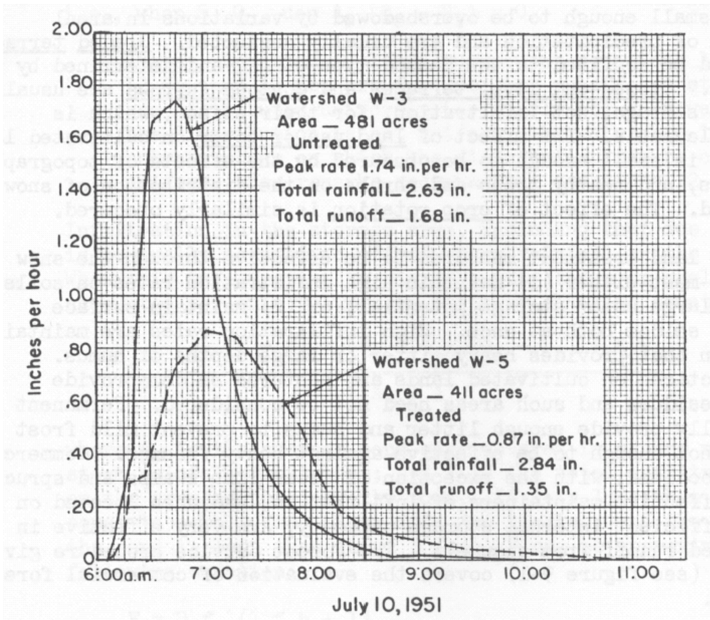

Figure 4.3 Effects of land use and treatments on lag (source: Allis, 1953)

An improvement for conditions where ridges and furrows are needed is to produce a series of cross ridges in effect damming the main furrow (tied ridges), Hudson, (1995). This produces a set of independent areas to hold rainfall and irrigation water. This approach may have value to prevent runoff in the summer months but is unlikely to be needed for winter grown crops. There is evidence from the Environment Agency that these have overtopped, washing out the tied ridge and producing erosive gullies. It is imperative, therefore, that they are engineered and used appropriately.

Leopold and Maddock (1954) stated that:
"improved management, including crop rotations, the actual sequence of planting various crops, the use of mulches, and other practices which tend to improve the tilth of the soil, is more effective in reducing storm runoff than the more readily observed practices such as terracing, contour cultivation, and strip cropping. These improved management practices are also more important in improving crop yields than are the changes in cultivation practices on the field. Thus, the effects of land management of greater magnitude with respect to storm runoff are those yielding their return primarily to the individual landowner. They are also the very practices which only the landowner himself can apply to the ground".

Retention structures. Castle *et al*. (1984) reported that:

"catch water ditches, which have for many years intercepted surface runoff at a field boundary, have been removed on many farms, as fields have been amalgamated to meet the needs of efficiency on large arable farms. Consequently the enlarged area allows a greater quantity of water to move down slope unintercepted, causing significant soil erosion problems even on fields with only slight slopes."

Field drainage linked with good cultivation practices and well-maintained channels can reduce peak flows after heavy rainfall. Rainfall is accepted into the soil moisture reservoir from which surplus water from previous rainfall events has been slowly discharged. This creates a buffer which reduces the effect of peak flow.

A simple calculation shows that for an area of 30 hectares, assuming a square catchment, a ditch along one side would be 550 m in length. A suitable assumption for a ditch with a cross sectional area of 1.5 m^2 would give a total ditch volume of 825 m^3 which is equivalent to a depth of water of 2.75 mm across the catchment.

In order to improve the drainage system, more intelligent system must be developed. One of these developed in North Carolina (Skaggs, 1993), is referred to as controlled drainage. This is where a structure is placed in the ditch or tile outlet, to manage the subsurface drainage outflows, such that at times of low to normal precipitation rates the system allows the fields to be effectively drained, whilst providing the buffer capacity. However when there are extended periods of high precipitation rates the drainage rate is reduced or closed. Current instrumentation, control and communication technology should enable simple systems to be developed to regulate the flow; this could be accomplished either automatically or by remote control. These could be referred to as Intelligent Drainage Systems.

Small ponds (reservoirs) and winter filled irrigation lagoons. Schwab *et al*. (1993) reported on two methods of headwater flood control namely:

- those that retard the flow or reduce the runoff by land treatment or ponds
- those that accelerate the flow by channel improvement.

Flow retardation is probably the most useful in agricultural situations, as it has the following benefits:

- All visible evidence or danger of the flood is removed
- The flow in the stream is more uniform, thus providing greater recharge of the groundwater and a more adequate water supply
- An important step toward the conservation of natural resources is achieved
- Higher crop production results
- A reduction in sedimentation in lower tributaries is accomplished

There are two main types of reservoir for storage. Detention storage and flood regulated storage. The principal difference is the detention reservoir operates automatically by discharging through one or more fixed openings in the dam, whereas the regulated reservoir discharges through adjustable gates. Flexibility of operation is the main advantage of the regulated reservoir and those of the detention reservoir are its simplicity and automatic operation.

In the UK, 25,000 m^3 is the maximum capacity allowed for an above ground lagoon, before the installation is classed as a large reservoir, needing full engineering certification (Reservoirs Act, 1975). For an on farm pond, i.e. one that is created below the ground level, there is no capacity limit as long as the structure is lower than the surrounding land. There would also need to be an overflow spillway and the outflow might be better engineered / controlled with either sluice boards or pumps. These could also be controlled automatically or by remote control.

A 30 hectare catchment with a 1 in 10 year return daily rainfall of 40 mm would need a storage reservoir capable of holding 12,000 m^3 of runoff (assuming 100% runoff). The current limit for above ground detention reservoirs that need no specialist construction is 25,000 m^3, which could store all the runoff from a similar size of catchment for the heaviest rainfall expected over 5 days for a 1 in 10 year event (77 mm). With good soil management above this reservoir, the area serviced could be several times that of the hypothetical 30 ha catchment. The size of the outflow pipe can be regulated to provide the desired out flow to match the hydrograph of the catchment(s).

4.4 Headwater management

The principal aim of any headwater soil management or runoff detention feature is to attempt to slow the outflow from the smaller sub catchments, and thereby reduce the peak of the hydrograph for the main catchment outflow. Different management techniques give different results to the hydrograph. These are illustrated in Figure 4.4; the diagrams on the right show techniques that will reduce the peak of the hydrograph so that shallow gradients, rough surfaces, storage, low density soil and longer pathways all reduce the peak.

Water, when it is moving, can be extremely erosive, causing scouring actions on the soil. By maximising infiltration through increased surface retention, the velocity of the water can be slowed so as to reduce its' erosive potential. Surface retention must be coupled with adequate subsurface drainage to constantly remove excess water from the soil profile. The critical aspect of these relationships is that all soils will have between 40 and 50% of their total volume filled with water at saturation; it is the difference in pore space between field capacity and saturation, referred to as drainable porosity, that is vital for the temporary storage of excess rainfall. Keeping the soil between permanent wilting point and field capacity allows for emergency buffering capacity up to saturation in difficult conditions.

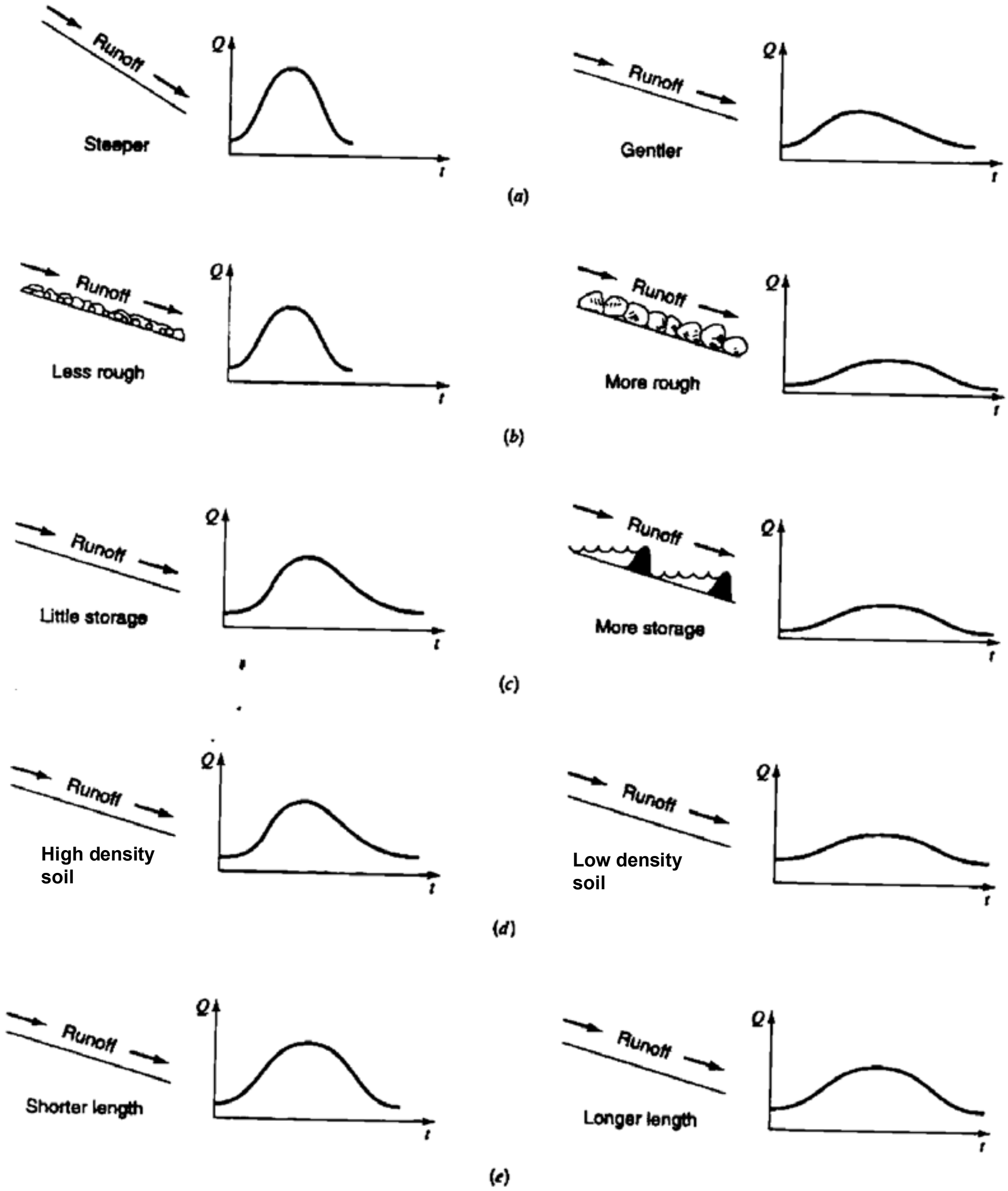

Figure 4.4 The effect of management practices on outflow hydrograph.

If this buffering capacity is inadequate then controlled runoff needs to be considered. Controlling the flow velocities and diverting it into detention reservoirs for slow release or away onto a sacrificial area are devices currently used in the Parrett Catchment described by Godwin and Dresser (2003), (e.g. Sowy River, Curry Moor and Hay Moor). If the infiltration rates, drainage, or the buffering capacity of the soil can be increased, or if storm water runoff and drain outflow can be held back in the upper catchments for a longer period whilst the peak of the hydrograph for the lower catchment subsides, then the flooding problems can be minimised.

4.5 Effects downstream

Schwab *et al*. (1993) presented data from the Tennessee Valley Authority, given in Figure 4.5, which shows the hydrographs of poor woodland that had been burned and grazed. After the land was retired from use, reforested and better managed, the peak flow for a similar storm 10 years later was only 15% of that before treatment.

The reverse is demonstrated where clear felling of a catchment at Wagon Wheel Gap in Colorado resulted in an increase in stream flow of 30 mm $year^{-1}$ or one sixth of the annual rainfall (Bates and Henry, 1928).

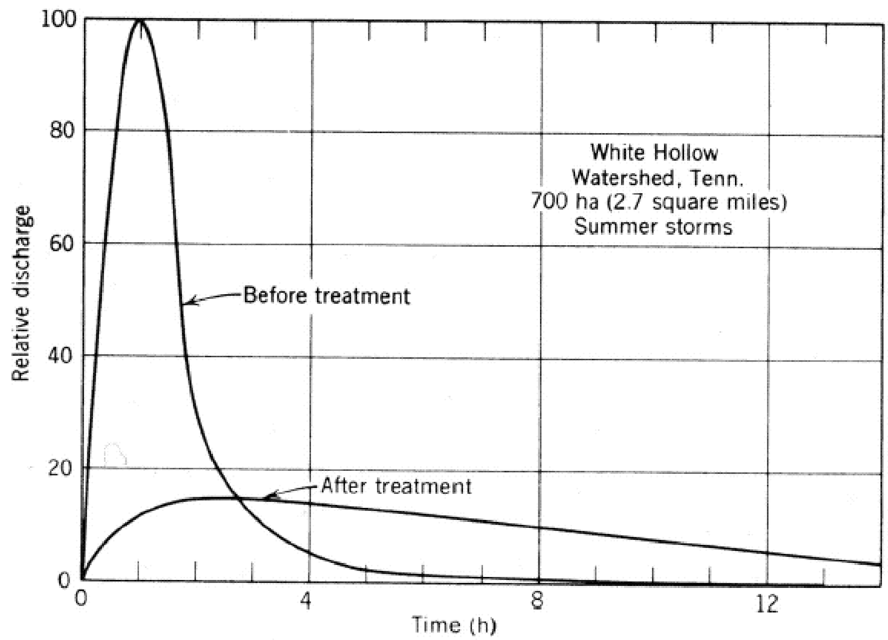

Figure 4.5 Effect of land management on flood flow (from Schwab et al., 1993)

Reservoirs for flood control reduce flood peaks, but not volume. This reduction in peak flow diminishes rapidly with distance downstream since the main stream receives an increasing percentage of its runoff from other tributaries.

Therefore, upper catchment/watershed management is vitally important to reduce cumulative effects in the lower catchment. The use of on farm storage ponds, ditches, and greater infiltration in the upper catchment reduce the peak flow of the hydrograph. The runoff or discharge from a storm event still has the same total volume, it is just released to the lower catchment at a lower rate, over a longer time period. This in turn is likely to reduce flood risk, erosion and sedimentation. Figures 4.6 and 4.7 show a hypothetical example of this, as described by Leopold and Maddock (1954). The figures show the effect of using dams to control the runoff from three 25 km^2 sub-catchments in a 150 km^2 catchment, for an event with 25 mm of rainfall in 4 hours.

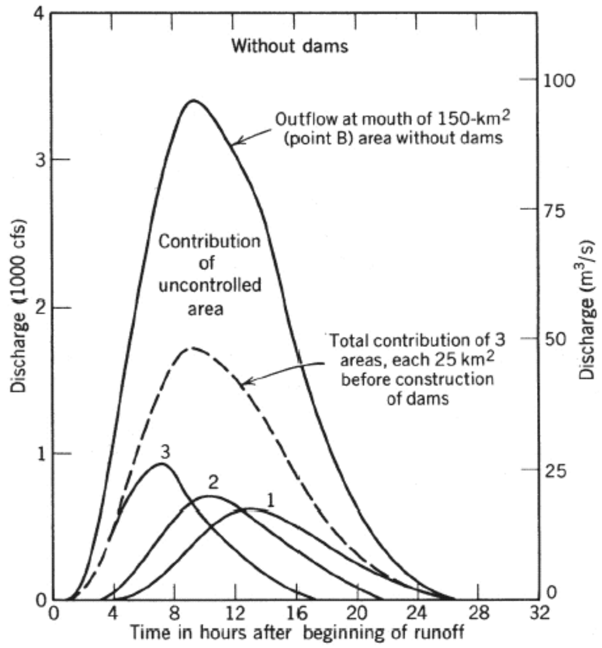

Figure 4.6 Runoff hydrographs without dams (from Leopold and Maddock, 1954)

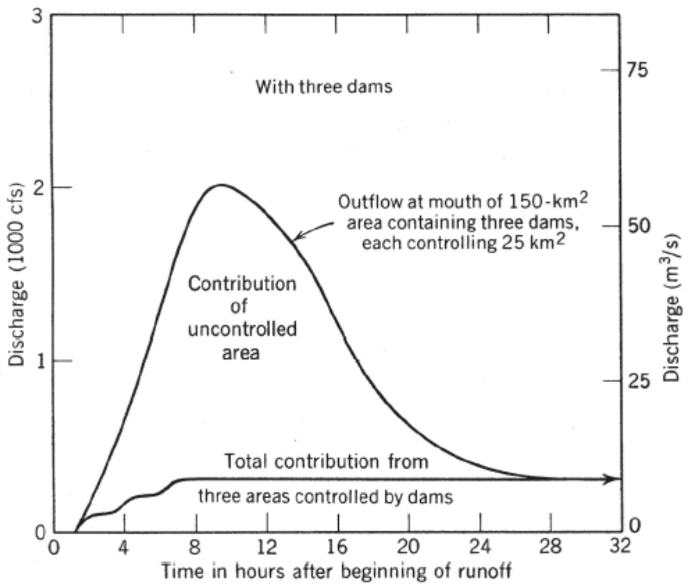

Figure 4.7 Runoff hydrographs with dams (from Leopold and Maddock, 1954)

5. Summary and conclusions

The total areas under arable, grassland and rough grazing have remained reasonably constant over the last 50 years. However, livestock densities, crop types and management practices have changed significantly. The key changes in arable cultivation have been a shift from spring to winter-sown cereals and the introduction of new crops, most notably maize and oilseed rape. Livestock numbers have risen significantly over the last century that, more recently, has been accompanied by an extended grazing season. There has also been an increase in the area of woodland, with an approximate doubling, mainly in the uplands.

In many cases, land use changes, and the accompanying management practices, have been linked to increased erosion and farm-scale runoff, and the degradation of soil structure. Of particular concern are practices that leave the soil surface bare or with little crop cover in the winter, especially if the soil has been worked down in to a fine tilth (for a seedbed). Other potentially damaging practices are husbandry systems that require the use of heavy machinery on the land, and also any actions that increase the surface and subsurface flow connectivity of the landscape, to give pathways for rapid runoff.

5.1 Best management practices

There are a number of mitigation strategies that can been proposed for reducing farm-scale runoff. These measures can be categorised as follows:

- Land use
- Providing increased protection to the soil surface
- Soil structural protection
- Reducing flow connectivity
- Increasing retention and storage

Land use

Runoff is more likely to occur in arable land, compared to grassland, especially where that grassland is carefully managed. This is because the soil management processes, including cultivation and harvesting, are subject to weather patterns and local damage (e.g. plough pan development). Conversion of arable land to grassland is, therefore, a potential mitigation option that will be applicable to specific soils and landscape conditions.

Runoff reduction in grassland is perhaps less difficult. It could include replacement of hedges and changes of grazing strategy. The main cause of compaction and runoff problems has been increasing stocking densities. There have been economic drivers for this, including headage payments. EU reforms, leading to area payments instead, could considerably reduce the pressure to retain high stocking rates. Reduction in the number of livestock will reduce treading and probably ultimately decrease runoff and flooding. Controlling the grazing locations, and compaction, caused by animals to areas of the field further up the field slope can allow the runoff to infiltrate into non-compacted areas of the field lower down the slope.

Lowering the watertable increases the soil strength, reflected by the penetration resistance. For grassland, this can prevent poaching if the watertable is kept at 0.5 m below the soil surface, which increases the soil strength by a factor of two. Sacrificing some of their least productive areas for sheep grazing, to copses and non-grazed areas, provides an ideal opportunity for the up slope runoff to infiltrate.

Outdoor pigs are a relatively new land use, and they provide a high risk of runoff and erosion. Specific measures need to be introduced to reduce the risk of runoff from outdoor pig production. The design of outdoor pig units should take account not only of ease of management, but also the area of land within and uphill of a unit likely to lead to the generation of surface runoff. The Environment Agency report suggest that vehicle access should be controlled and that the inclusion of specially designed buffer features in the layout of units may be of benefit in reducing the potential for surface runoff.

New crops required for energy and biomass such as Miscanthus and Short Rotation Coppice (SRC) can afford a significant amount of protection to the soil surface.

Soil surface protection

A vegetative cover on the soil, especially during periods of heavy and/or intense rainfall, helps to bind the soil particles together, increases surface roughness and absorbs the kinetic energy of incident rainfall. Transpiring crops remove water from the soil profile, thereby making it less susceptible to surface runoff generation.

Novel, but practical, techniques to maintain over-winter crop cover on susceptible soils should be considered. For example, the use of vegetation (e.g. grass, natural regeneration set-aside or cover crops) could be targeted to vulnerable areas in catchments where runoff and erosion are generated. An example would be maize, where the use of an understorey, e.g. Italian ryegrass, within the crop canopy that grows on after the crop has been harvested greatly reduces surface runoff. The Maize Growers association now recommends that this practice be adopted (and also that the crop is harvested earlier in autumn than at present). The application of mulches to maize crops has also been shown to be beneficial in reducing runoff.

Soil structural protection

Increasing the organic matter of the soil opens pathways and improves infiltration into the soil. Avoidance of over-cultivation and over-compaction (leading to plough pans), together with the incorporation of crop residues, will help to encourage better infiltration into the soil surface in cropped areas.

Reducing loads, decreasing tyre pressures and increasing tyre widths, to lower the stress exerted on the soil, can only be beneficial to soil structure. The use of Terra tyres and tracked vehicles, especially on soils with an existing poor structure, can help to alleviate some of these problems. The impact of tillage operations used to prepare a smooth, level seedbed in order that faster and more accurate sowing techniques can be adopted, are deleterious to soil and water conservation and should be minimised or avoided.

Flow connectivity

Surface runoff should be controlled, both in terms of generation and its conveyance, once initiated. Maintenance of ditches and culverts and installation of underdrainage has been shown to work in certain areas. Cross-slope interceptors, such as grass buffers, ditches or hedges would slow surface runoff and increase the likelihood of infiltration. They have the effect of reducing the slope length.

Large cracks have a significant influence on the hydrologic characteristics. These cracks fill and empty at very low tensions, and provide rapid water removal from the upper soil layers. There is a need to balance the presence of these cracks, with the need for effective sub-surface drainage. If not managed correctly, improved drainage provided by the open leg slot of mole drainage can cause peak runoff rates to be increased and the time to peak to be reduced. With correct management, however, the drainage can help provide buffer capacity to absorb rainfall and thereby reduce peak flows and the drained water can be released into lower sections of the catchment in a controlled manner. It may not be practical on economic grounds to alleviate the reductions in drainage status, due to an overall deterioration in the UK drainage stock. However, in clayey soils, action should be undertaken to halt the decline in drainage status by encouraging farmers to maintain drainage outfalls and to check to ensure that there is an adequate connection between the surface soil and the sub-surface drainage system.

Where possible, contour cultivations should be undertaken on land susceptible to surface runoff and erosion. Runoff and erosion in tramlines running up and down the slope could be resolved by cultivating the tramline with a single tine or chisel plough to break up the compaction and increase both surface roughness and infiltration. However, care is needed when managing the surface compaction made by wheelings, which generally run up and down the slope. Whilst simply loosening the soil surface can increase infiltration, gully erosion can occur in the longer-term. Using wider tyres (0.5-1 m wide) will reduce the contact pressures and rutting, increase trafficability and reduce runoff.

Retention and storage

Increasing the roughness of the soil surface by mouldboard ploughing, or by creating small depressions, has been reported to provide temporary storage for runoff of between 9 and 16 mm.

A general return to smaller fields, with boundary hedges and ditches should have a beneficial impact on runoff, and the banks or ridges often associated with hedges will also impede runoff.

Retention structures such as small ponds and reservoirs also retard the flow or reduce runoff.

5.2 Conclusions

There are many methods available to control runoff, which include: manipulating surface crop cover (e.g. vegetation/cropping, stock control, timeliness of intervention), soil management (e.g. soil looseness, wheelmark control, contour tillage, underdrainage status) and headwater management (e.g. field storage, ditch storage, ponds/lagoons, field boundaries and hedge replacement). Slowing runoff, or holding it back in the headwaters, is largely dependent on vegetation cover and favourable storage conditions, and should be considered within a flood mitigation strategy.

However, effects are also very variable. For example, the trend of simply changing from spring to autumn cropping of cereals has been reported to lead to some increase in the likelihood of runoff, whereas the practice of harvesting sugarbeet and other crops much later than usual, and with contract machinery, has led to a much increased likelihood of runoff. In considering what crop to grow, and how to manage the soil, drainage and landscape, feasible crop rotations must be considered.

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