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COFORD's activities are part-funded under the operational Programme for Agriculture, Rural Development & Forestry, 1994-1999.

First published in 1999 by National Council for Forest Research and Development, National University of Ireland, Belfield, Dublin 4, Ireland.

ISBN 1 902696 04 2

Title: Forest Drainage Engineering
A Design Manual

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Citation: Forest Drainage Engineering
A Design Manual
Mulqueen, Rodgers, Hendrick, Keane, McCarthy, COFORD, Dublin

Design: Keystrokes Ltd., Dublin

FOREST DRAINAGE ENGINEERING

A DESIGN MANUAL

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February 1999

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Acknowledgements

This project was part-funded by The National Council for Forest Research and Development, COFORD, under the European Union (EU) STRIDE Forestry Sub-Programme.

The authors are grateful to their present and former colleagues who assisted both directly and indirectly in work that contributed to the contents of this design manual. The help of Patrick Naughton, James McHale and Brian Gallagher, research assistants in the Civil Engineering Department, National University of Ireland, Galway, is acknowledged. The work of Ms Patricia Lynch of COFORD is also gratefully acknowledged.

1. INTRODUCTION AND SCOPE

1.1 Introduction

Many marginal lands in Ireland can be highly productive for forestry; these include wet mineral soils and some peatlands. However, in the wet Irish climate, frequent saturation and waterlogging of these lands, which adversely affect forestry production, can take place due to a variety of soil drainage problems. These problems have a number of causes, which should be first identified and analysed in order to drain the land successfully. This manual facilitates the correct identification of drainage problems and the rational design of solutions.

Cultivation and forest drainage can have far-reaching effects not only on the productivity and profitability of the forest itself, but also on the overall catchment in which the forest is located. For example, cultivation and forest drainage can have implications for:

- wildlife, including fish;
- quality and quantity of water for drinking;
- industrial uses of water; and
- recreational uses of water.

The concerns on the effects of forestry on water quality have led to Irish forestry and fisheries interests coming together to issue guidelines in relation to best practices for forest establishment and management (Forestry and Fisheries Guidelines, Forest Service, 1991). As well as fisheries, other Guidelines take into account forestry interactions with archaeology and landscape.

In the Forestry and Fisheries Guidelines (1991), specifications are given for drainage and ground preparation, particularly within riparian and aquatic zones. These specifications depend on the local designation of sensitive sites and the reader should take these into consideration when using this manual. Grant and premium payments are dependent on compliance with the Guidelines.

Properly designed and executed forest drainage, which is essential for crop establishment, tree stability, harvesting and profitability in many areas, should not be in conflict with recreational, landscaping and other non-wood beneficial uses of forestry. The design techniques in this manual should contribute to the achievement of effective drainage in forest lands without adverse impact on the local environment.

1.2 Scope

This manual describes the drainage problems that occur in Irish conditions and how they should be investigated and solved. Each drainage problem is site specific and should be examined individually in relation to design. Designs are also provided for the minimisation and control of soil erosion.

In Chapter 2 the benefits of drainage and control of soil erosion are discussed. Drainage problems and their solutions are described in general terms in Chapter 3; this chapter also includes a description and discussion of erosion and its control. The detailed investigative and design techniques for well-defined problems of drainage and erosion are given in Chapter 4.

Technical assistance is strongly recommended in cases of uncertainty in relation to problem diagnosis and detailed design.

2. EFFECTS OF DRAINAGE

2.1 Windthrow Reduction

Where the soil is waterlogged, depth of tree rooting is shallow resulting in increased likelihood of windthrow (Rodgers *et al.*, 1995). Windthrow is the largest single source of economic loss in Irish forests and often occurs just before the trees reach full maturity. Suitable site preparation techniques that include properly designed drainage can reduce the occurrence of windthrow and lead to increased crop yields.

In all plantations, profitability is very closely related to rotation length and hence top height. The probability of windthrow increases with top height, particularly when crops reach heights in excess of 15 m. In Sitka spruce crops, in particular, this is the critical time in the crop rotation. The proportion of sawlog sized wood relative to the less valuable pallet and pulp wood increases as top height increases from 15 to 25 m. The relationship between discounted revenue and top height is depicted in Figure 1. It can be seen that the discounted revenue/ha at 39 years, when the trees have a top height of 24 m, is approximately twice that at 29 years, when the trees have a top height of 18 m.

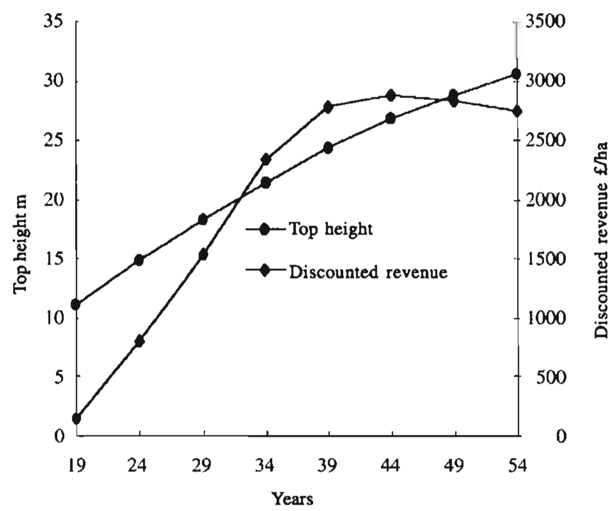


Figure 1: Height and revenue growth over time in a Sitka spruce crop, Yield Class 20

2.2 Trafficability

In addition to improving rooting depth and anchorage against winds, a properly installed and maintained forest drainage system will improve trafficability. A closed subsurface drainage system, such as mole drainage, leaves a practically undisturbed ground surface, which facilitates movement of harvesters and forwarders. Furthermore, lowering the water-table increases soil strength, thus improving machine manoeuvrability.

2.3 Soil erosion

Effective drainage can greatly reduce overland flow and associated sheet erosion. It can also reduce soil disturbance by forest machinery and reduce erosion from these effects. Properly designed drains for embankments and roads in afforested areas can abate erosion from these sources. However, unless properly designed, drainage itself can cause significant erosion, particularly from the base and sides of open drains. These problems are addressed in Sections 3.6 and 4.4.

2.4 Environmental benefits

The following environmental benefits can accrue from effective drainage of afforested areas:

- reduced suspended solids because of reduced overland flow;
- greater yield of water to rivers and streams in summer;
- reduced flooding in winter;
- reduced acidity; and
- reduced windthrow and associated soil damage.

3. LAND DRAINAGE PROBLEMS

The objective of forest drainage is to prevent the soil water rising into and saturating the root zone and waterlogging the soil. By maintaining the water-table below the root zone, drainage promotes deep rooting, improves tree anchorage and strengthens the soil. It may also prevent the build-up of soil pore water pressure, which can occur during windy conditions, resulting in hydraulic fracture of the soil and windthrow.

To be successful, forest drainage must drain away the surplus water rapidly and must be designed against the background of the cause of saturation and waterlogging. As an aid in visualising the cause of the saturation and waterlogging, it is useful to classify land drainage problems as follows:

- impermeable layer;
- high water-table;
- hillside seepage;
- springs and artesian seepage; and
- peatland drainage.

3.1 Impermeable layer

The impermeable layer that causes a drainage problem may be thick or thin. In the case of a thick impermeable layer the soil usually consists of a shallow topsoil of about 150 mm depth overlying a layer of clay or silt, which can vary in thickness from 1 to 20 m (Photograph 1). Mole drainage and subsoiling (Figure 2), and ripping in the case of hard layers, are the solutions to thick impermeable layer problems.

Photograph 1. A comparison of an impermeable soil (A) and a free-draining soil (B). In A, a thin (150mm) dark organic topsoil overlies a dark grey cohesive, plastic and impermeable clay. In B, a brown brittle topsoil of about 600 mm overlies a light grey brittle loamy subsoil.

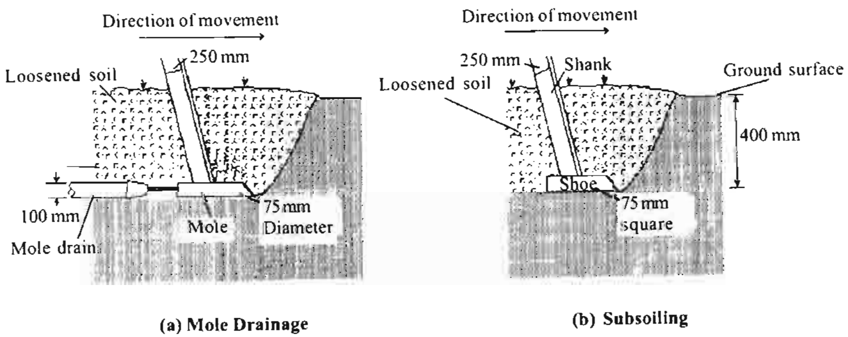


Figure 2: (a) Mole drainage and (b) subsoiling illustrated

Thin impermeable layers comprise iron- and fragi-pans; iron-pans are usually only a few mm thick but fragi-pans may be 300 mm or more in thickness. Depending on the depth and hardness of the soil, subsoiling or ripping are used to break the thin impermeable layer and promote drainage to a deep water-table (Figure 3).

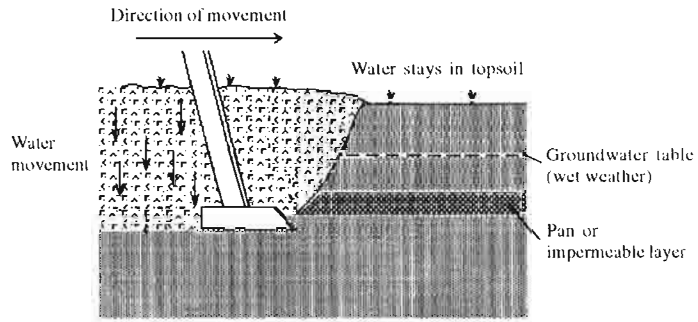
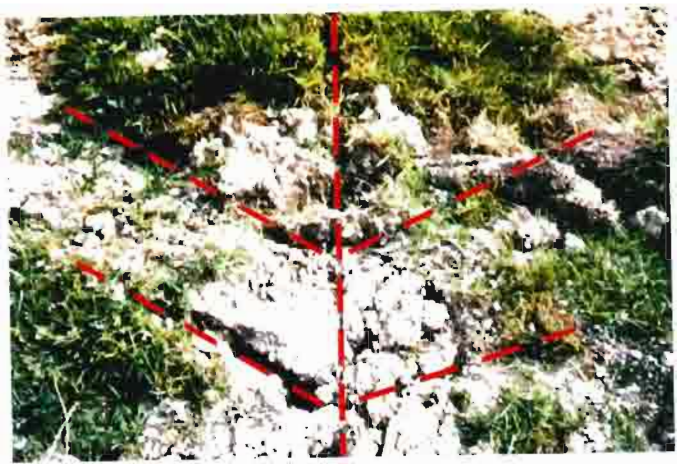


Figure 3: Use of a subsoiler to break a thin impermeable layer

In subsoiling and moling, a subsoiler shoe or mole, respectively, is drawn through the soil at a depth of about 400 mm. A subsoiler shoe leaves a discontinuous channel, which is partly filled back with soil while a mole leaves a continuous subsurface drain channel. The shoe or mole is mounted on a leg attached to a beam, which is free to float (Figure 4).

A ripper is distinguished from a subsoiler mainly in that it has a wider (usually 50–75 mm) and longer leg. The leg is commonly mounted on a parallelogram frame attached to a tracked tractor and controlled by hydraulic rams. The parallelogram configuration makes possible a constant rake angle in work.

The objective of mole ploughing, subsoiling and ripping in thick impermeable layers is to install closely spaced drainage channels and to fracture and loosen the soil (Mulqueen, 1998) to make it permeable (Figure 2). To effectively fracture and loosen the soil, mole drainage, subsoiling and ripping must be carried out when the soil is dry (Photograph 2). This fracturing and loosening enables the excess soil water to percolate rapidly into the drainage channels through the cracks and discharge into collector drains. In mole drainage, near circular continuous drain channels (Figure 2(a)) are formed, while in subsoiling and ripping the channels are discontinuous due to soil falling back into them (Figure 2 (b)). Mole drainage is therefore to be preferred and even where conventional mole ploughs don't work, the shank and shoe of the ripper can be modified to install mole drains. A tractor mounted mole plough is illustrated in Figure 4; this can be easily converted to a subsoiler by replacing the mole with a square shoe.



Photograph 2. Fractures in dry soil induced by the leg of a mole plough. The plough leg makes a vertical slit in the soil. The direction of travel is from the bottom of the picture to the top. Fractures open up on both sides from the slit at an angle of about 45 degrees and point in the direction of forward travel in a herringbone fashion.

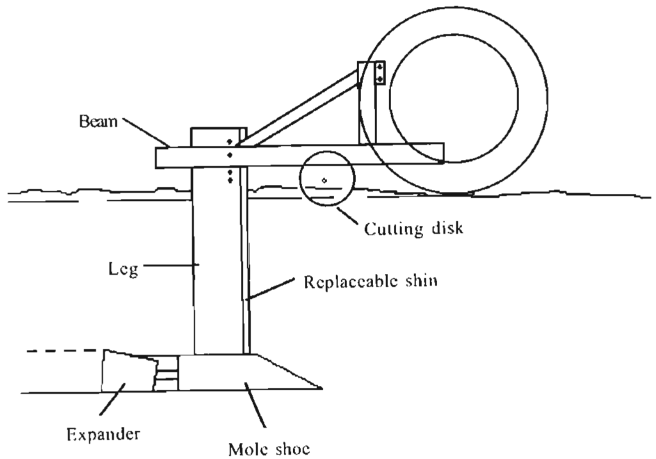


Figure 4: Illustration of a mole plough mounted on a 3-point linkage.

Wings can be fastened to subsoiler and ripper shanks to increase the extent of soil loosening as illustrated in Figure 5. In some situations the trees are planted in the loosened soil and in others in mounds placed on the loosened soil.

Drainage methods for impermeable layer problems and their typical locations are given in Table 1.

Table 1: Drainage methods for impervious soils

Soil type	Soil preparation/drainage method	Typical areas
Clayey type soils, for example: surface water gleys and peaty gleys	Moling and collector drains	Cavan, Castlecomer Plateau, Leitrim, Monaghan and Sligo
As above but with many stones	Ripping, collector drains and mounds	Some drumlin areas
Surface water gleys high in silt	Moling with closely spaced collector drains and mounds	Clare, North Kerry and West Limerick
Stony, thick compacted or cemented soils, for example: podsols, podsolised gleys, peaty gleys high in silt and fine sand	Ripping, collector drains and mounds	Ballyhoura Hills, Slieve Aughty and Nagle Mountains
Thin compacted or cemented soil layer, for example: fragi- or iron-pans, at depths greater than 600 mm with permeable soil below	Ripping	Donegal, West Cork, West Mayo, West Waterford and Wicklow
Thin compacted or cemented soil layer at depths less than 600 mm with permeable soil below	Subsoiling; ripping if stony	Reclaimed agricultural land, for example: compacted arable land; shallow iron-pans

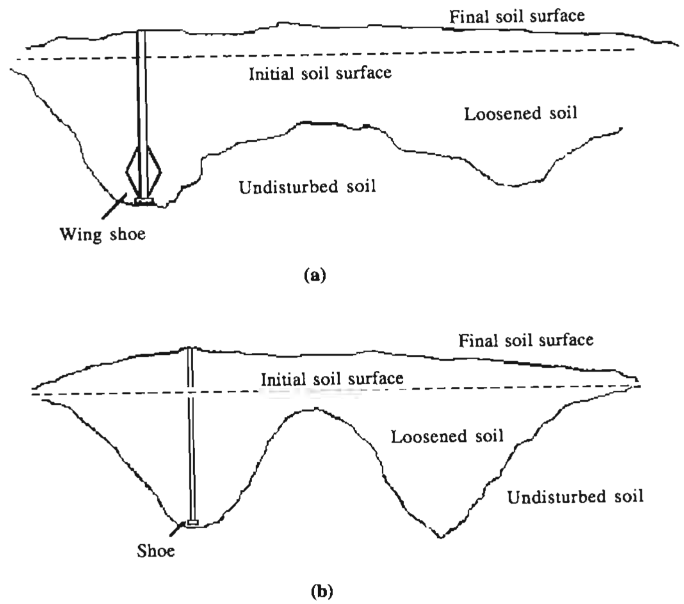


Figure 5: Illustration of soil disturbance by a subsoiler (a) with and (b) without wings

3.1.1 Mole drainage

Mole drains are generally drawn at a uniform depth of 375 - 450 mm with the greater depths (450 mm) in soils with deeper topsoils (250 - 300 mm). Spacings are 750 - 1000 mm. In practice, the spacings are 1000 mm to facilitate planting at 2000 mm centres. A worked example is given on pages 29 to 31 and a typical layout of a mole-drained field is shown in Figure 6.

An open collector drain is excavated at the foot of the field to a minimum depth of 650 mm and the resulting spoil is spread. Mole drains are then drawn up and down slope at the design depth and spacing. Immediately afterwards, open collector drains are excavated across the slope at a slight angle to the contour on the up-slope side of all graded out fences and at design spacings of 10 – 40 m. The spacing of the collector drains is determined by the three factors listed below.

1. The stability of the mole channel: the more stable the mole channel the more distant the spacing of the collector drains. The stability of the mole channel may be known from previous drainage for agriculture and may also be determined from local experience. A remoulded ball of subsoil, which holds its shape for more than one day immersed in a bucket of water, may indicate stable mole channels; in contrast, intact specimens of fragi-pans disintegrate on immersion in water.
2. The slope of the land: steeply sloping and flat lands require a closer spacing of collector drains, for example, 10 m. Long mole drains in steeply sloping lands are prone to erosion and in flat lands to waterlogging; it is advisable to mound flat sites that have been mole drained to achieve satisfactory survival and growth.
3. The stone content of the soil: mole drainage channels in stony soil tend to be discontinuous where stones are dislodged by the plough; as a result stony soils require a closer spacing of collector drains.

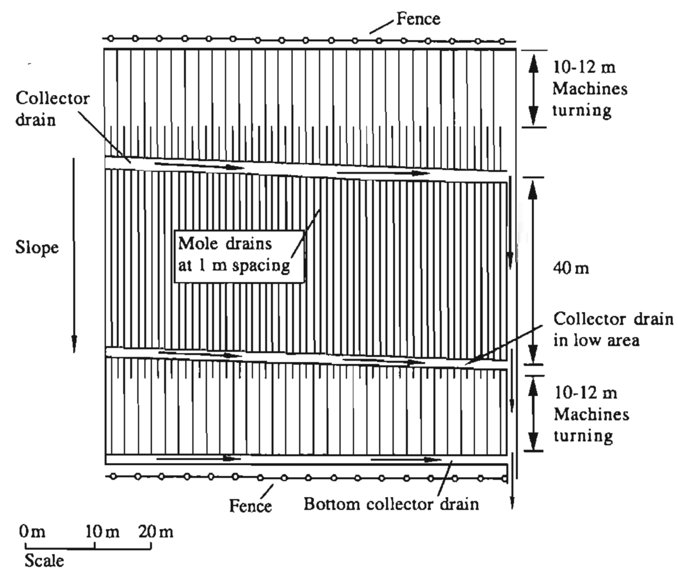


Figure 6: A mole drainage layout with moles drawn up and down slope

The drain spoil should be spread or used for mounding especially on the flatter areas (see above). The outlets of mole drains that have been closed by excavating the collector drains must be reopened on the up slope side and on both walls in flat sites. In low spots, it is necessary to install spur drains or open additional collector drains. The tree should be planted as indicated in Figure 7 (a).

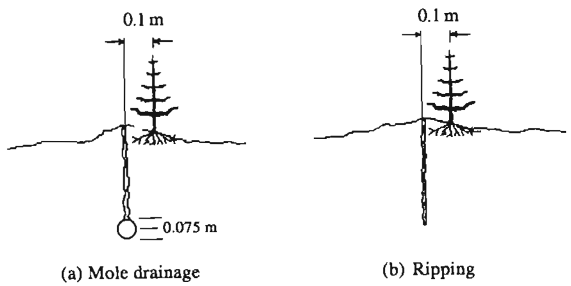


Figure 7: Recommended planting positions in relation to mole drains and rip slots

3.1.2 Ripping or subsoiling

Ripping is typically used on compact hard sandy/silty soils and on stony clayey soils that cannot be moled. The ripper is fitted with a replaceable shoe that bursts the overlying soil, increasing its permeability; the use of wings near the foot of the ripper also increases the bursting effect. In a typical soil, ripping is carried out at a depth of 500 mm and at spacings of 750 mm - 1000 mm. The depth of ripping should be greater if a deep peat layer covers the impermeable soil. Usually, the ripping is first carried out up and down slope. The collector drains are then cut across slope, at a slight angle to the contour. They are excavated to a minimum depth of 150 mm below the ripping depth and at spacings of 5 - 20 m apart depending on the slope and permeability. Because of the discontinuous nature of the drain channel after ripping or subsoiling, the steeper the slope and the more permeable the loosened slab of soil, the more distant the collector drain spacing. The shank and shoe of the ripper may be modified to install mole drains.

The spacing of the collector drains can be designed for the soil conditions at the site in accordance with the procedures for hillside seepage given in Chapter 4. During excavation of the collector drains, mounds should be placed at 2 m centres using the excavated material.

When ripping or subsoiling is used, where an iron pan or other compacted layer occurs, at least 90% of the layer should be broken in the loosening operation. The depth of ripping should be a minimum of 75 mm deeper than the impermeable layer and the spacing is typically 1000 mm. In small areas where a deep impervious layer is below the shoe of the ripper shank, deep digging may break this layer. Normally, no collector drains are required; however, an interceptor drain may be needed at the upper end of the site to collect overland flow from outside areas. Trees should be planted as shown in Figure 7 (b).

3.2 High water-table

High water-tables occur in low-lying areas where deep permeable soils overlie impermeable layers. Usually, this problem can be solved by using equally spaced parallel drains 1.0 - 1.5 m deep. Drain spacing depends on the soil permeability which may be determined by field tests or estimated from experience. Typical values of drain spacings are 10 - 20 m. The excavated drain spoil can be used to make mounds. This problem occurs in the flood plains of rivers and adjoining lowlands and is common in midland counties such as Kildare and Offaly.

3.3 Hillside seepage

Hillside seepage occurs when water flows down slope through a permeable soil layer overlying an impermeable soil layer (Figure 8).

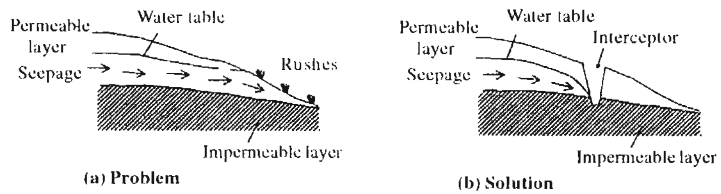
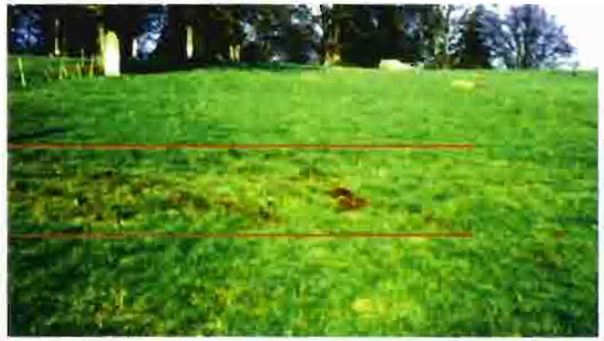


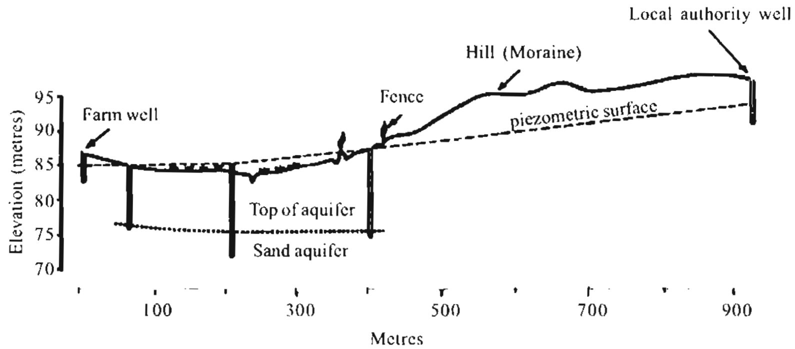
Figure 8: Hillside seepage problem and drainage solution

If there is a reduction in slope or a rise in the impermeable layer, the water will seep out above the ground surface (Photograph 3). This causes waterlogging at the soil surface and commonly occurs where rushes are found growing on the lower slopes of dry hills. This problem can be solved by installing an interceptor drain along the line of seepage with additional drains down slope as required, at about 8–12 m centres. The drain should penetrate the impermeable layer where feasible and typical drain depths could be down to 1.5 m. Minor slips in the sides of the drain occur during and immediately after excavation until the soil stabilises; any slip material should be cleared away to prevent blockage of the drains. The excavated spoil should be used down slope of the interceptor drain for planting mounds. Above the interceptor drain, since the water-table is low, trees can be planted directly into the soil. Adequate outfall from the drainage system must be available or put in place. Hillside seepage occurs in drier drumlin areas such as Cavan and Monaghan, in Wicklow, west Limerick and elsewhere.



Photograph 3. Hillside seepage often occurs as a wet band across a hillside. The seep zone is enclosed by the black contour lines. As a result of the seepage break-out, the wet band has been rutted by machinery and rush growth is evident.

3.4 Springs and artesian seepage



Transect 1. A cross section of an artesian seepage condition near Enfield, County Meath. The piezometric surface as measured in 5 wells, shows a groundwater gradient towards the low ground with the central well showing an artesian (above ground surface) head.

A spring arises wherever water, pressurised and flowing through a deep permeable layer, such as sand, gravel or weathered rock (Transect 1, Photograph 4), breaks up through the overlying surface layer through a fissure or fissures in the soil (Figure 9). The spring may show as a strong and often perennial flow from a point location or as a weak leakage from a soft localised marshy area, say 3 m in diameter, with an elevated bulging surface confining a liquefied soil. Springs are often found in groups along contour lines separating rising ground from flat ground and may also be scattered throughout adjacent valleys.

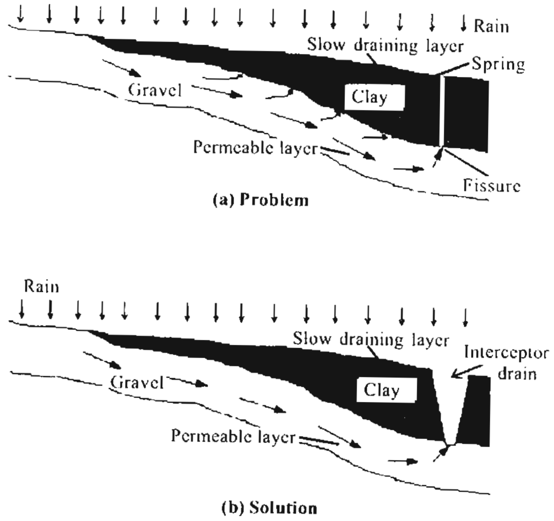


Figure 9: Occurrence and drainage of a spring and seepage.

Photograph 4. The artesian (central) well of Transect 1 showing a free discharge of 4m³/hr at ground surface

Artesian seepage is a more diffuse upward leakage of pressurised water from a sub-surface water-bearing layer to the surface layers of soil (Transect 1; Photograph4).

Test holes should be excavated by hydraulic digger along the wet line where the water breaks through the soil surface to determine the sub-surface conditions that give rise to the springs or seepage. The presence of yellow flag (wild iris) is a good indicator of the break-out of the pressurised water. An interceptor drain should penetrate into the permeable layer carrying the water. Typical drain depths are 1-2.5 m. Excavation costs and risk of failure increase at greater depths. Drainage is not practicable where outfalls at a depth of 1 m or more are not available. Drain wall slips can occur during excavation and the slipped soil may have to be removed until the wall stabilises. Above the interceptor drain, no site preparation is normally necessary. This problem occurs typically in lowlands associated with hills and mountains.

3.5 Peatland drainage

Peats range from permeable to practically impermeable. Permeable peats are normally found where the upper peat layers have been removed (cutover/ cutaway); nearly impermeable peats occur in blanket bogs. Permeable peats are drained in the same way as the soils with a high water-table. Equally spaced parallel drains, 1.1 m - 2.0 m deep, are excavated at about 10 - 20 m spacings. Such deep drains are required to allow for settlement that occurs due to the drainage. The trees can be planted on the flat without mounds. However, if mounds are used, it is essential that soil with a high pH, such as marl, should be avoided, as it will adversely affect tree growth.

There are considerable difficulties in maintaining a low water-table in practically impermeable bogs. Low water-tables can be achieved by putting in drains at spacings of 1.0 - 4.0 m. This is only economical for small areas. The tunnel plough offers another alternative but its application is limited to firm peats that are low in fibre and practically free of tree stumps. The tunnel plough drains have typical spacings of 2 m with a depth of 750 mm. Trees may be planted in the plough ribbon. Other options include ploughing and mounding. However, there are growth and stability problems, and subsequent timber extraction difficulties associated with these techniques, especially with ploughing.

3.6 Control of erosion

Afforestation and reforestation can have environmental impacts on streams, rivers and lakes through erosion and sedimentation and through direct effects of forest growth on the water bodies themselves. These can impact on the beneficial uses of the waters for fisheries, wildlife, water supply, and for recreation. This section addresses the most significant of these potential impacts and how these can be prevented or reduced to insignificant levels. Two approaches are adopted to control and limit erosion:

1. design drainage, so that there will be no scour in the drain channel; and
2. estimate the amount of soil erosion from drains and minimise this erosion by suitable choice of the flow parameters of velocity and hydraulic gradient using theoretical concepts.

Procedures for the design of settlement ponds to trap sediment are provided. Potential sources of erosion and contamination of soil and water bodies are then discussed and guidance is provided on the use of practical measures to control these.

Sedimentation in afforestation and reforestation sites can arise directly as a result of accelerated erosion. Such erosion is defined as erosion above normal or geological levels, brought about in this case by cultivation, drainage and harvesting works, and road works necessary for access and the harvest and transport of wood. As a result of these works, the vegetative protective cover of the soil can be broken or destroyed and bare soil exposed to the forces of wind driven rain and overland flows on the surface and in channels (rills), drains and watercourses. Detached sediment can be transported into watercourses, streams and rivers where it can harm fish, spawning and nursery areas and interfere with the beneficial uses of water for water supply, navigation and hydroelectric power.

Apart from these direct effects, sediment in streams and rivers can assimilate chemicals and wastes and in this way act as a carrier and storage medium for phosphorus, ammonia, organic compounds and microorganisms. Erosion and sedimentation can be significant in drains, where large areas of a catchment are prepared for planting at one time, on sloping roads and on unprotected steep cuts and embankments. Gully erosion is a localised but more severe form of erosion where large flows are concentrated.

3.6.1 Guidance on the practical control of erosion and sedimentation

Both the production and release of eroded sediment should be controlled. Measures can be taken to:

1. prevent and limit erosion and the generation of sediment; and
2. induce the release of unavoidable sediment from the run-off water before it gains entry to a stream or river.

3.6.1.1 Cultivation

Only the minimum cultivation necessary should be employed. For gley and shallow peaty gley soils, effective mole drainage practically eliminates erosion by promoting infiltration; erosion from collector drains on stiff clays is negligible. On peaty soils, spaced furrow ploughing should be shallow (e.g. 200 - 300 mm to remain in the strongly cohesive layers (due to roots). However, where furrows have a drainage function to lower the water-table they must be deep to allow for settlements. On shallow peaty soils over loosened (ripped or subsoiled) mineral soils, ploughing should also be shallow to minimise the exposure of more erodible mineral subsoils, except where the furrows have a drainage function. Where feasible, all ploughing should preferably be carried out at a small (acute) angle down slope of the contour (e.g. 0.3 - 3%) to reduce the velocity of any water that might flow in the furrow; where this is not feasible, water drops should be employed in erodible soils. For buffer strips and areas adjoining special areas of conservation, cultivation should be confined to a minimum, for example, mounding only or no cultivation. In the case of mounding only, ditches from which the mound material was excavated should be graded gently where possible (e.g. 0.3 - 3%) and they should be of short length in loose and low cohesion soils e.g. less than about 50 metres.

3.6.1.2 Drainage

For practical reasons, mole ploughs and rippers must be drawn up and down slope. Collector drains collecting drainage water from mole drained and ripped land (Table 2) should be excavated at a small acute angle to the contour (0.3%-3% gradient) to minimise velocities of flow (Kinori, 1970). Main drains, which take the discharge from collector drains, should be provided with water drops and rock armour where there are excessive gradients.

Channels in erodible soils which drain into the aquatic and riparian zones should stop before the riparian zone and be allowed to fan out and flow overland over a buffer strip. Such areas should be uncultivated, and left unplanted. The buffer strip may be even or irregular in width and may also be placed on critical slope areas of the field. Typical widths of buffer strip are indicated in Table 3. Ideally, the width of buffer strips should be designed against the type of cultivation, erodibility of the soil, gradient and catchment area of the drains. The aim should be to encourage a strong growth of ground vegetation to trap sediment. The drain should taper out onto the buffer strip.

Silt traps or sedimentation ponds may also be used to trap sediment and debris such as needles. The pond may be designed to hold the sediment over the life of the forest or may be designed with limited storage, in which case machine access is required to enable the accumulated sediment to be removed. The excavated sediment should be carefully disposed of and not necessarily tipped or dumped in the most convenient place. The design of sedimentation ponds requires experience with similar forested areas and therefore machine access should always be provided to allow for excavation of sediment. Sedimentation ponds should be securely fenced for safety.

Table 2: Allowable non-erosive velocities (m/sec) in open watercourses

Soil Texture	Bare Channel	Channel Vegetation		
		Light	Medium	Dense
Sand, silt, sandy loam, silty loam	0.5	0.5	0.6	0.9
Silty clay loam, sandy clay loam	0.6	0.9	1.2	1.5
Clay	0.8	0.9	1.5	1.8

Table 3: Recommended widths of buffer strips (Forestry Commission, 1993)

Stream width (m)	0.1	1- 2	>2
Buffer width (m)	5	10	20

3.6.1.3 Forest roads

Forest roads should be planned to minimise erosion and sedimentation which might damage streams. The following guidelines assist in meeting these objectives:

1. forest roads should be built away from riparian zones whenever possible;
2. the catchment into roadside drains should be minimised by controlling their lengths by diversions and by diverting surface run-off up-slope;
3. where the gradient cannot be minimised or watercourses join at different elevations, then grade stabilisation structures may be employed: these include small dams to reduce the flow velocity, culverts under roads, headwalls and splash plate assemblies to control down-cutting where water from a tributary at high level discharges into a lower open watercourse, rocks should be used to dissipate the energy in water drops where headwalls and splash plates are not provided; roadside drains should discharge onto buffer strips or into sedimentation ponds when they are likely to carry significant sediment;
4. embankments and cuts should be battered to angles less than the angle of repose to minimise slips; all surface run-off should be diverted away from slopes and cuts;
5. erosion from roadside embankments and cuttings can be minimised by installing interceptor trenches filled to soil surface with gravel and piped if necessary along the slope at a small gradient; seed and fertilise exposed slopes or slurry seed in dry weather to hasten establishment of vegetation;
6. forest roads should be constructed in dry weather;
7. maintain and keep clear all roadside drains to avoid overflows;
8. maintain a cross camber or use ramps to minimise erosive water velocities on roads, fill wheel ruts; and
9. inspect forest roads regularly and carry out repairs and maintenance as required.

3.7 Other Environmental Aspects of Afforestation

3.7.1 Water flow in and from forests

In relation to water flow in and from a forest, three zones of the catchment are recognised in relation to streams, rivers and lakes (Forestry Commission,

1993). These are the aquatic zone, the riparian zone and adjacent land. The aquatic zone is frequently or permanently under water and includes streams, rivers, ponds and lakes. The riparian zone comprises land immediately adjoining the aquatic zone and influenced by it. The adjacent land comprises the bulk of the catchment.

Rainfall may be retained in the forest canopy and other vegetation and may pass through to the soil. Some of the rainfall that is intercepted is directly evaporated from the leaves and branches. The remainder passes through onto the soil and leaves the soil as drainage, surface run-off or evapotranspiration depending on the soil, rainfall rate and season. Impervious soils, shallow soils on impervious bedrocks and some impervious peats exhibit peaky surface run-off which tends to be brown and acidic. Drainage from deep free draining and some imperfectly drained soils tends to be more even, clear and less acidic.

In the riparian zone, soils in wet weather are often at or near saturation. As a result, the soils may be peaty gleys and peats, and the vegetation is commonly rush-infested, wet woodland or poached rushy grassland with buttercups. Forest management can protect such zones where conservation is considered desirable.

The aquatic zone has importance in relation to fisheries, wildlife, recreation and water supply. Small headwater streams often serve as spawning grounds for salmon and trout. Such spawning grounds may be seriously damaged by sediment or debris from tree felling or by changes in flow induced by new large watercourses or fallen trees. The aquatic zone can be protected by judicious design of cultivation and drainage and by suitable arrangements for felling, such as felling in sensitive areas in dry summer weather only. Water yield from heavily forested catchments tends to decline due to greater interception as the canopy closes (Table 4).

Table 4: Rainfall, evapotranspiration and run-off from typical catchments

Land use	Rainfall mm	Evapotranspiration mm	Run-off mm	Run-off[1] %
Grassland	1200	400	800	66
Spruce forest	1200	550	650	54

[1] As a percentage of rainfall

M. Ryan

3.7.2 Potential problems: water and afforestation

1. Ploughing and drainage of complete catchments can result in an increase of peak flows of 20 - 30 % from moderate rainfalls, increasing the potential for frequent flooding. There does not appear to be any increase from large rainfalls.
2. New inflows of water can change the stability of a stream or river channel.
3. Erosion from poorly laid out cultivation, drainage and roads can greatly increase sedimentation and turbidity of water. High turbidity can decrease light penetration reducing biological productivity and fish feeding and migration. On settlement, suspended fine sediment can damage spawning areas by blocking oxygen supply to young fish; it can also form a coating on plants and feeding materials for invertebrate fauna. Increased sedimentation can lead to reduction of storage in rivers and reservoirs.
4. Increase in discharges can lead to an increase of discolouration of water from peaty catchments. This could decrease light penetration.
5. Nutrient enriched (particularly with phosphorus) run-off could result in an increase in the growth of algae. Applying fertiliser in dry weather to dry soil could reduce this effect to insignificant levels.
6. Acidification can result from an increase in hydrogen ion concentration, which can result in increasing solubility of aluminium. This could arise after clearfelling and can be avoided by phasing clearfelling. It is also possible to place limestone gravels in the outfall streambed in non-erosive areas to reduce the hydrogen ion effect.
7. Fuel oils, chemicals and pesticides can gain entry to waters due to accidental spillage or spraying of watercourses. For drinking water the concentration of many individual pesticides may not exceed 0.1 mg/m^3. Care should be taken with refuelling and in preventing spillages; special care should be exercised in spraying near watercourses, streams and rivers, by, for example, leaving a buffer zone unsprayed. These precautions can avoid and limit potential contamination.

3.7.3 Afforestation in relation to streams and rivers

The structure and composition of riparian vegetation greatly influences the adjoining and downstream aquatic environments. The location and species composition of forests in the riparian zone should be selected so that the aquatic environment and water quality are protected and enhanced where possible.

- The planting location, layout and management should maintain open and partially wooded conditions so that bank vegetation thrives. This minimises the potential for bank erosion and opens the water to sunlight.
- By maintaining about half the length of a stream or river open, the remainder is under partial shade from trees and shrubs. Heavy shade casting trees such as spruce, oak, beech should be mixed with lighter foliaged trees such as birch, ash and willow.
- Management such as pruning and removal of undesirable trees should be carried out as required to maintain the specified riparian and aquatic conditions.

4. DETAILED DESIGN PROCEDURES

4.1 Depth and spacing of drains

Soils with high water-tables are in need of drainage to prevent soil water rising into the root zone in wet weather. The depth and spacing of the drains to control the rise of the water-table depend on the nature of the soil and the soil water conditions. It is necessary to correctly identify the drainage problem in order to prescribe a design solution that will be successful. The test pit is the key to successful diagnosis of the drainage problem. Where there are shallow topsoils, a hand-dug pit may suffice but machine excavated pits are more revealing and economic. Deep pits in wet soils should be fenced off or should be closed, before leaving the site. By noting the nature and structure of the soil with depth and the nature and positions of soil water flows, the drainage problem type can be defined.

Drainage problems can be grouped as follows:

- thick impermeable layers such as silts and clays with a shallow (150 mm) topsoil;
- thin impermeable layers such as iron pans;
- high water-tables found in lowlying flat lands where a thick permeable layer, up to 10 m or more, overlies an impermeable layer;
- hillside seepage where a downslope flow of water through a permeable top layer of soil breaks out on lower slopes;
- springs and artesian seepage caused by the breakthrough of groundwaters under high pressure onto the soil top layers; and
- peatland drainage problems where the peat controls the flow of the soil water.

Soils with thick impermeable layers can only be drained by closely spaced parallel drains at shallow depth after soil loosening. Soils with thin impermeable layers are drained by breaking the thin impermeable layer with a subsoiler or ripper. High water-table soils are drained by equally spaced parallel drains at medium or large depths; the greater the depth the more distant the spacing. Hillside seepage is drained off by an interceptor drain along the upper boundary of the water breakout and additional interceptor drains down slope as required. Springs and artesian seepages are drained by medium to deep drains in or connected to the water-bearing layer. Peatlands are drained in a manner similar to mineral soils depending on the type and nature of the drainage problems.

4.2 Permeability measurements

For drainage to be successful the soil must be sufficiently permeable to allow a quick outflow of water from the soil to the drains. To design the drain spacing it is necessary to know the permeability of the soil, that is how fast the soil transmits excess water. For drain spacings at realistic intervals, the soil must have a permeability greater than 0.1 m/day. Soils with permeabilities lower than 0.1 m/day requiring drainage must be loosened and cracked to increase their permeability values.

With experience, permeability values can be estimated to sufficient accuracy by examining the soil for its silt and clay content, plasticity, stickiness and structure. Plastic, sticky soils and dense tight soils have very low values, and loose non-plastic soils have moderate to high values. Typical permeability values are given in Table 5 and Table 6 shows a classification of permeability values.

Table 5: Typical permeabilty (K) values for soils and gravels

Description	K m/day
Topsoil	0.5 - 1.0
Blanket peat	0.01
Woody peat	0.5 - 1.0
Reed or sedge peat	0.005 - 0.1
Cracked sedge peat	0.1 - 1.0
White marl	0.03 - 0.05
Alluvial mud	0.001 - 0.01
Loam – depending on the degree of compaction	0.001 - 1.0
Sandy loam	0.5 - 5.0
Silty loam – depending on the degree of compaction	0.001 - 1.0
Clay loam – depending on the degree of compaction	0.0001 - 1.0
Compacted sandstone & shale subsoil	0.001 - 0.1
Tight boulder clay	less than 0.001
Soil after ripping, subsoiling or moling	0.5 - 1.0
Silty sand (0.02 - 0.2 mm particle size)	0.1 - 1.0
Sand (0.1 mm particle size)	1.0
Sea sand (0.3 mm particle size)	10.0
Sand (2 mm particle size)	100.0
Sand (2 – 6 mm particle size)	1000.0
Gravel 75% (10 - 20mm), 25% (2 – 6 mm)	5000.0
Gravel 90% (10-20 mm), 10% (2 – 6 mm)	15000.0

It is desirable to carry out *in situ* permeability tests in the field to obtain permeability values for soils with the following drainage problems:

- high water-table;
- hillside seepage; and
- springs and artesian seepage.

Table 6: Classification of permeability

K m/day	Class
≤0.01	Very slow
0.01-0.1	Slow
0.1-0.3	Medium slow
0.3-1.0	Moderately rapid
1-10	Rapid
>10	Very rapid

4.2.1 Square hole method for measuring permeability above a water-table

The square hole method is a technique used to measure the permeability of soils above a water-table. A square hole of 150 mm side is excavated carefully with a heavy-duty spade to a depth of at least 100 mm into the layer under investigation. The base of the hole is levelled as best possible. The hole is then cleaned and brushed to remove any glazing on the sides so that the test reflects the undisturbed soil properties. Then 500 ml of clean water is carefully poured into the hole and the time at which this occurs is noted. The water is allowed to percolate completely out of the hole and when it is all gone the time is recorded.

The permeability (K) of the soil can be got from the following formula:

$$K = \frac{b}{4.t}.\ Ln[1 + \frac{4}{b}.h(t_1)]$$

where:

t is the time taken for the hole to empty;

b is the side dimension of the hole; and
$h(t_1)$ is the height of the water above the base of the hole at the start of the test.

For the test condition described above, the equation reduces to the form:

$$K = \frac{25}{t}$$

where t is expressed in minutes and the value of K is given in m/day. If t is equal to 100 minutes, K will be 0.25 m/day.

4.2.2 Pit bailing method for measuring permeability in saturated soils

The pit bailing method (Bouwer and Rice, 1983) is a technique that may be employed when the water-table is high. This consists of excavating a circular pit of 1 m radius with sloping sides to a depth, L_C, below the water-table into the layer for which permeability is to be measured (Figure 10). The water in the excavated pit is allowed to rise to the water-table level over a period of up to 48 hours. The water in the pit is then lowered rapidly with a pump or excavator bucket to a depth, Yo, below the water-table. The depth of the water level in the pit, Yt, is then measured after a time t, which can be up to 120 minutes, has elapsed. Before the test pit is opened, a trial pit is excavated nearby to determine the depth to the impermeable layer. Knowing this depth, it is possible to evaluate the distance, D, from the bottom of the test pit to the impermeable layer. From the above information a value of the permeability of the soil can be calculated.

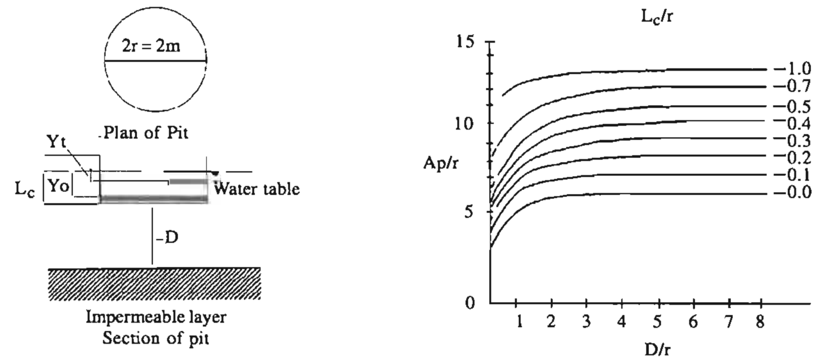


Figure 10: Illustration of pit bailing method and graphical solution for determining permeability

Typical example of the pit bailing method:

Radius of the pit, r = 1.0 m
Depth below water-table, L_c = 0.3 m
Depth of impermeable layer below the base of the pit, D = 5 m
Yo = 0.160 m
Yt = 0.110 m
t = 30 minutes

Solution:

$$\frac{L_c}{r} = \frac{0.3\,m}{1\,m} = 0.3$$

From Figure 10:

$$\frac{Ap}{r} = 9.3$$

The permeability, K, is given by

$$K = \frac{\pi.r}{\frac{Ap}{r}.t} \cdot Ln\left[\frac{Yo}{Yt}\right]$$

$$K = \frac{\pi.1.0}{(9.3).(30)} \cdot Ln\left[\frac{0.16}{0.11}\right]$$

= 0.00422 m/min = 6.1 m/day

4.3 Worked examples for drainage design

4.3.1 Impermeable layer (mole drainage)

Hydraulic design of a typical example (Figure 11):

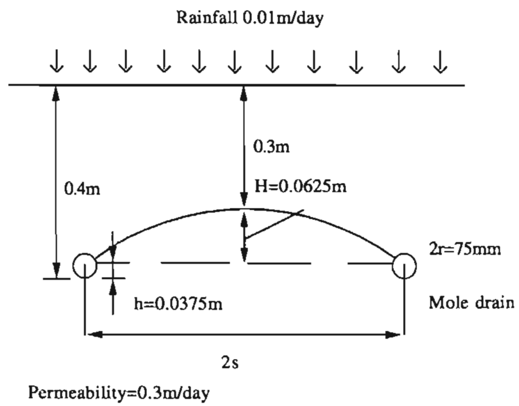


Figure 11: Mole drainage example

Depth of drain = 0.4 m

Diameter of drain = 75 mm

H = 0.0625 m

h = 0.0375 m

Rainfall, R = 0.012 m/day

Soil permeability, K = 0.3 m/day

Solution:

$$\frac{H}{h}\left[\frac{K}{R}-1\right] = \frac{0.0625}{0.0375}\left[\frac{0.3}{0.012}-1\right] = 40$$

$$\frac{h}{2r} = 0.5$$

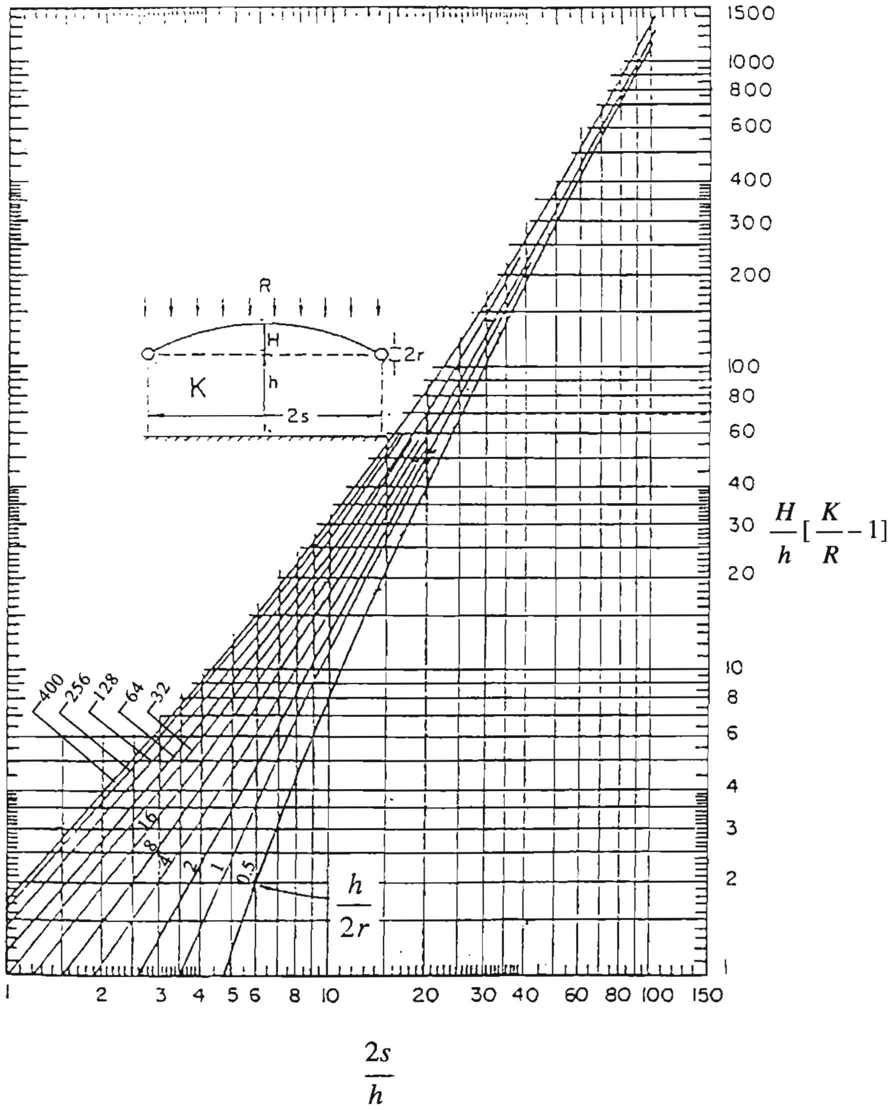


Figure 12: Graphical solution of drain spacing

From Figure 12:

$$\frac{2s}{h} = 20$$

Therefore the spacing between the drains, 2s = 20h = 0.75 m but can be extended to 1 m to facilitate planting.

4.3.2 Hillside seepage

Design for a typical example (Figure 13)

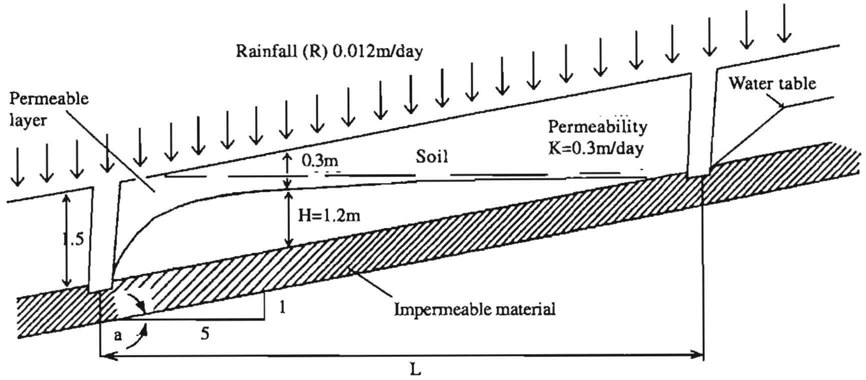


Figure 13: Hillside seepage

Rainfall, R = 0.012 m/day
Soil permeability, K = 0.3 m/day
Ground slope is 1 vertical to 5 horizontal
Depth to impermeable layer is 1.5 m
Water-table to be maintained at a depth of 0.3 m below ground surface

Solution:

$$\frac{R}{K} = \frac{0.012}{0.3} = 0.04$$

$$Tan\ \alpha = \frac{1}{5} = 0.2$$

H = 1.2 m

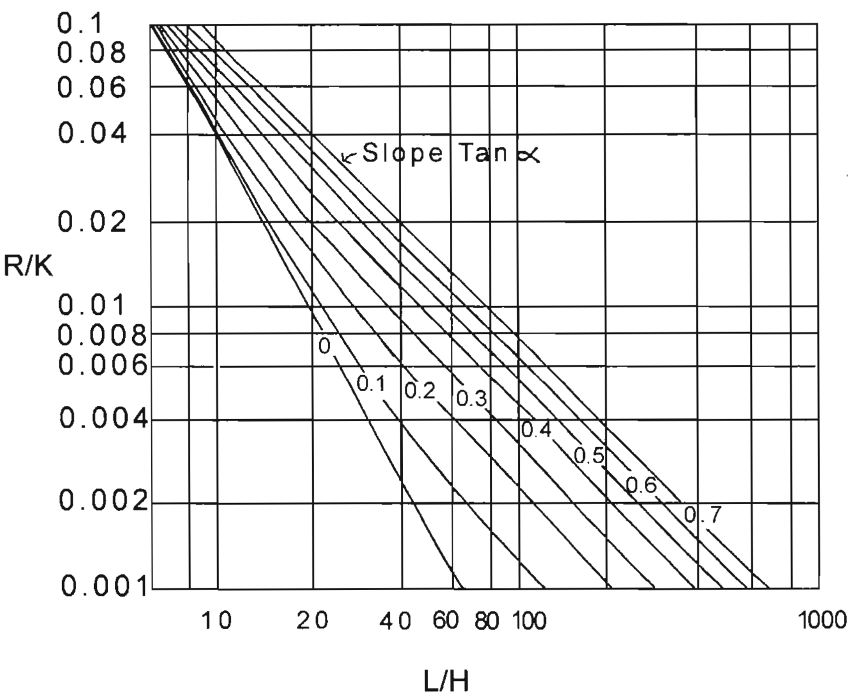


Figure 14: Graphical solution for drainage of hillside seepage

From Figure 14:

$$\frac{L}{H} = 11$$

Therefore the drain spacing, L = 11.H = (11). (1.2 m) = 13.2 m.

4.3.3 Springs and artesian seepage

In a slowly draining soil underlain by a stratum of high permeability, it is assumed that vertical flow occurs in the top layer and horizontal flow in the permeable layer. The spacing of the drains can be obtained from the Ernst equation (Ernst, 1956 and 1962) which is written as follows:

$$h = R\frac{Dv}{Kv} + R\,\frac{L^2}{8\cdot Kh\cdot Dh} + R\,\frac{L}{\pi\cdot Kr}\cdot Ln\left(a\cdot\frac{Dr}{U}\right)$$

where:

h is the total hydraulic head or water-table height, in metres, above the level of water in the drain
R is the design rainfall in m/day
L is the required drain spacing in metres
Kv is the permeability for vertical flow in m/day
Kh is the permeability for the horizontal flow in m/day
Kr is the permeability for the radial flow in m/day
Dv is the thickness, in metres, of the layer through which vertical flow occurs
Dr is the thickness, in metres, of the layer through which radial flow occurs
Dh is the thickness, in metres, of the layer through which horizontal flow occurs
U is the wetted perimeter of the drain in metres
a is a geometry factor for radial flow and is equal to 1 when the drains are placed in the bottom, more permeable layer, which commonly holds.

Design for a typical example is shown in Figure 15:

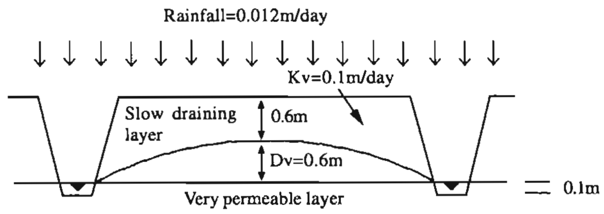


Figure 15: Seepage on the flat

h = 0.6 m, R[1] *= 0.012 m/day, Kv = 0.1 m/day, Kh = Kr = 100 m/day*
Dv = 0.6 m, Dh = 0.3 m, U = 0.3 m, a = 1, Dr = 0.2m

Solution:

By inserting the above values in the Ernst Equation, the following is obtained:

$$0.6 = \frac{0.012*0.6}{0.1} + \frac{0.012*L^2}{8*100*0.3} + \frac{0.012*L}{3.14*100}*Ln\left[\frac{1*0.2}{0.3}\right]$$

$$0.6 = 0.072 + 5.0 * 10^{-5}L^2 + 1.55 * 10^{-5} * L$$

[1]Where water is flowing into an area, this water must be added to the rainfall

As the final term in the above equation is small, it can be neglected so that the equation simplifies to:

$0.53 = 5.0 \cdot 10^{-5} \cdot L^2$

Therefore the drain spacing, L = 102 or 100 m in practice.

4.3.4 High water-table

Design of a typical example as in Figure 16:

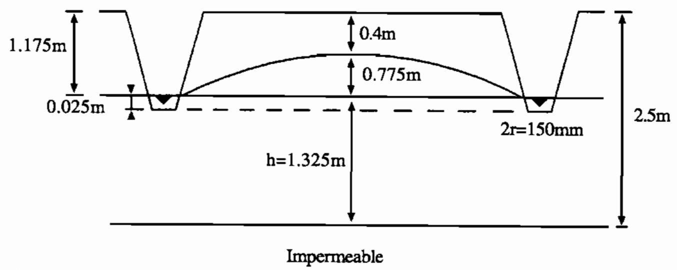


Figure 16: High water table

Depth of drain = 1.2 m
Effective width of drain invert = 0.150 m
For an impermeable layer 2.5 m below ground surface with a design water-table 0.4 m below ground surface, the following apply:
$H = 0.775$ m
$h = 1.325$ m
Rainfall, $R = 0.012$ m/day
Soil permeability, $K = 0.3$ m/day

Solution:

$$\frac{H}{h}\left[\frac{K}{R}-1\right] = \frac{0.775}{1.325}\left[\frac{0.3}{0.012}-1\right] = 14$$

$$\frac{h}{2r} = \frac{1.325}{0.150} = 8.83$$

From Figure 12:

$$\frac{2s}{h} = 7.75$$

Therefore the drain spacing, 2s = 7.75.h=(7.75). (1.325) = 10 m

4.4 Worked examples for erosion control

4.4.1 Sheet erosion

When water flows over soil, it exerts a drag force on the soil particles with which it comes in contact. Sometimes this drag force is great enough to dislodge some of these particles, transport and later deposit them downstream. This is soil erosion. Two types of erosion may be distinguished: sheet erosion and channel (rill or drain) erosion. Sheet erosion arises from the detachment of soil particles by the impact of raindrops (often accelerated by wind) on exposed soil surfaces and their transport in overland or sheet flow. Sediment in overland flow may be referred to as wash load because of its very fine nature. Rill and drain erosion is the detachment and transport of soil particles by a flow of water concentrated in a channel.

Sheet erosion may be estimated from equation [1] from Schwab *et al.* (1993):

$$D_s = K_s.\ i^2.\ S_f \qquad [1]$$

where:

D_s = sheet erosion rate in kg/m^2. s
K_s = sheet erodibility of soil in kg. s/m^4
i = rainfall intensity in m/s
S_f = slope

Equation [1] indicates that sheet erosion rate is a function of the soil erodibility (K_s) and slope (S_f) and of the square of the rainfall intensity (i). A few intense storms can contribute 90% or more of the sediment. Erosion is most serious under heavy rainfalls on long slopes having high run-off soils with erodible top layers.

Consider an intense storm of 10 mm rain in one hour, and a sheet erodibility of soil, K_s of 1x10^6 kg.s/m^4 on a uniform slope of 10%, then the erosion rate, D_s, is 0.77 mg/m^2.s or 28 kg/ha.hour.

4.4.2 Drain design to control erosion

In forestry, drain erosion is likely to be the dominant form of erosion, especially where drainage channels with steep slopes are installed; however, unlike sheet erosion the effects of drain erosion are local but can be significant. Gully erosion is caused by local scour where run-off is concentrated in channels; it depends on the soil resistance, the drainage area and the slope of the channel. Additional sediment can arise from bank slippage and erosion (for example undercutting of the side wall) and bed load transport.

Sediment load may be classified from a practical point of view into wash load and bed load. Practically all the wash load comprising fine sediment is carried in suspension and is responsible for natural turbidity often seen in rivers during and soon after flood conditions. Bed load is that portion of the sediment particles found in shifting portions of the drain or channel bed.

From the point of view of erosivity, soils may be classified as non-cohesive and cohesive. Non cohesive soils are comprised of discrete particles such as gravels, sands and silts which are not strongly bound to neighbouring particles; their movement in response to erosive rainfall/water depends only on their size, density and shape. On the other hand, cohesive soils are resistant to initial movement in response to erosive forces because of the strength of cohesive bonds between the particles. Cohesion may be due to a root network in topsoil, clay content, chemical bonding and/or tight packing in well-graded soils.

Few data exist on drag stress and permissible velocities in relation to erosion.

The equation which was most commonly used in the past to predict erosion in drains and rills is (Kinori, 1970):

$$F = \gamma . R . J \qquad [2]$$

where:

F = the drag stress (kN/m^2)
γ = the unit weight of water (= 10 kN/m^3)
R = the hydraulic radius (m) of the rill or drain (cross sectional area of flow/wetted perimeter)
J = the hydraulic gradient

In rills and drains where the flow depth is shallow compared with the width of the water flow, the hydraulic radius may be replaced by the depth of flow. Following on an extensive field survey, Fortier and Scobey (1926) published a table of maximum permissible velocities and drag forces in canals at incipient scour or erosion for different soil types. A selection of their values (with modifications) is shown in Table 7. While there is no theoretical support for the data in Table 7, they are based on data supplied by experienced irrigation engineers and should be useful for simple design. Sediment from rills and drains is much coarser than that from overland flow.

Table 7: Drag stress and permissible velocities at incipient scour (Fortier and Scobey, 1926) for clean drain water and drain water with colloidal silts

Soil type	Drag stress F_o [1] N/m^2		Velocity v_o m/s	
	clean	silty	clean	silty
Fine sand, sandy loam	1.47	3.43	0.50	0.76
Silty loam, loam	2.45	7.36	0.69	1.00
Clay, fine gravel	3.43	7.36	0.76	1.50
Mixture of silt and gravel	11.77	21.58	1.22	1.68
Stiff clay, gravel	14.71	32.36	1.50	1.68

[1] The subscript $_o$ refers to incipient scour

The data in Table 7 can be used to design the gradient of drains for forestry in the following manner:

consider a trapezoidal drain with an invert 150 mm wide and a side slope of 1/2 [horizontal/vertical (H/V)] in a sandy loam soil. From Table 7, values of drag stress and permissible velocity at incipient scour for waters with colloidal silts are 3.43 N/m^2 (3.43/1000 kN/m^2) and 0.76 m/s respectively. From [2] the gradient at incipient scour is:

$$J_o = F_o/(\gamma . R_o) \qquad [3]$$

R_o is calculated from:

$$R_o = [d. (b + m.d)]/[b + 2d. (1 + m^2)^{0.5}] \qquad [4]$$

where:

d = depth of water flow in metres
b = width of invert in metres
m = cotangent of the angle the drain sidewall makes with the horizontal.

Let:

b = 0.15 m;
d = 0.02 m;
m = 0.5 (side batter of 1/2);
γ = 10 kN/m^3;
R_o from [4] = 0.016 m.

Then:

J_o = 3.43/[1000. 10 . 0.016] = 0.021 (2.1%).

Where such gentle longitudinal gradients are impractical on sloping lands, energy can be dissipated by water drops suitably placed in the drain; water drops fall onto inverts protected by rock armour. The discharge from the above drain is (0.76 . area of flow) = (0.76 . 0.0032 m^3/s) = 0.0024 m^3/s = 210 m^3/day. Such a flow would discharge from 1 ha of land when the run-off is 21 mm/day from a heavy rainfall.

In most cases in forestry the depth of drain required to control the water-table will take precedence over the size of drain and hydraulic radius necessary to transport the water.

4.4.3 Rate of erosion from drains

From 1972 onwards, Yang and others (Yang, 1996) concluded from a study of a large set of data that unit stream power is the dominant factor in determining total sediment concentration of alluvial and gravel bed rivers. Later, Moore and Burch (1986) extended the range of application to overland (sheet) flow and to rill or channel erosion. The latter can be extended to drain flow erosion. Yang (1996) defines the unit stream power as the time rate of dissipation of potential energy per unit weight of water; it equals the product of the average velocity and the slope of the energy line. While the theory applies to soil particles that are dispersed and free to collide with one another in suspension, it also applies to aggregated soils provided that the aggregate diameter is substituted for the particle diameter. For a full understanding of the theory, a knowledge of channel hydraulics is required; even without this understanding the equations can still be used to predict the rate of erosion in the manner shown below.

The steps in determining the erosion rate are: first, determine the unit stream power; then, calculate the concentration of sediment in the flowing water for this unit stream power; finally, calculate the quantity of eroded particles per unit time.

For drain flow, the unit stream power can be calculated from:

$$V.\,J = (Q/N)^{0.25}\,.\,(J^{1.375}/n^{0.75})\,.\,w \qquad [5]$$

where:

V = average velocity of water in the drain (m/s)

J = slope of the energy line

V. J = unit stream power (m.kg)/(kg.s)

Q = total water discharge (m^3/s) from an area of land

N = number of equally spaced drains draining the same area

n = Manning's roughness coefficient

w = drain shape factor

$$= \{[(a + z)^{0.5}]/[a + 2(z^2 + 1)^{0.5}]\}^{0.5} \qquad [6]$$

for a trapezoidal drain with a = top width/depth ratio of flow and z = drain side slope; in a rectangular drain z = 0.

When the width to depth ratio exceeds 2, the geometry of the drain has little effect on the value of the shape factor (w). Trapezoidal drains can be approximated by rectangular drains for this reason (Moore and Burch, 1986). According to Yang (1996), the most efficient channel with minimum energy dissipation is one with a = 2 for a rectangular section and 2.858 for a parabolic section drain (Moore and Burch, 1986). The most efficient shape factor (w) for rectangular and parabolic drain sections is 0.6.

The concentration of sediment can be estimated from (Yang, 1996):

$$\log C_t = A + B \log [(V.\,J - V_{crit}.\,J)/v] \qquad [7]$$

where:

C_t = total sediment concentration (ppm by mass) excluding wash load from overland flow;

A = dimensionless parameter reflecting flow and sediment characteristics = 5.0105 for overland and drain flow (Moore and Burch, 1986);

B = dimensionless parameter reflecting flow and sediment characteristics = 1.363 for overland and drain flow (Moore and Burch, 1986);

V. J = unit stream power (m/s)

V_{crit}. J = critical unit stream power at incipient motion (m/s); Moore and Burch (1986) found that this can be approximated by a constant of 0.004 m/s for cohesionless soil;

v = fall velocity of the soil particle (m/s).

After the concentration of sediment is known, the erosion rate in each drain in a given storm can then be estimated by:

$$Q_s = \rho . (Q/N). C_t \quad [8]$$

where:

Q_s = the quantity of soil eroded in each drain in unit time (kg/s)
ρ = the bulk density of water (1000 kg/m^3)
Q = the water discharge from a slope with N equally spaced drains (m^3/s).

Few data exist in relation to erosion from drains and overland flow in Ireland and further research in this area is recommended.

The rate of erosion in a trapezoidal or rectangular drain in medium fine sand (for example many sea and dune sands) is now calculated for the following conditions:

d_{50} of fine sand	= 0.2 mm;
sediment fall velocity (v)	= 0.024 m/s;
slope (J) of drain	= 0.04;
Q	= 0.0013 m^3/s;
Manning's coefficient (n)	= 0.03;
number of drains (N) crossing the slope	= 10;
V_{crit}. J (Moore and Burch, 1986)	= 0.004 m/s.

The unit stream power for flow in a trapezoidal or rectangular drain section based on the above data is:

$V. J = (Q/N)^{0.25}. (J^{1.375}/n^{0.75}) . w$
$V. J = (0.0013/10)^{0.25} . [(0.04)^{1.375}/(0.03)^{0.75}] . (0.6) = 0.0105$ m/s
$\log C_t = 5.01 + 1.363 \log [0.0105/0.024 - 0.004/0.024] = 4.236$
$C_t = 17249$ ppm
$Q_s = 1000. (0.0013/10). 17249. 10^{-6} = 0.00224$ kg/s

Similar calculations for aggregated clay showed a 1 to 1 relationship between observed and calculated sediment concentrations (Moore and Burch, 1986). If the rate of drainage in the example above (Q = 0.0013 m^3/s) is sustained over 10 hours of a day, it amounts to about 5 mm drainage from 1 ha. The amount of medium fine sand sediment deposited over this period amounts to 0.8 t/ha; if drains are spaced at 8 m, there are about 1200 m drain/ha and the erosion is about 0.67 kg/m. As practically all soils in forestry have some cohesion with a much higher critical unit stream power at incipient motion and a higher fall velocity, the erosion rate in forest drains is less at the same gradient; in stiff clay soils with cohesions in the range 20 - 40 kPa, erosion is negligible. Erosion from forest drains is mainly confined to sandy and silty

soils of low cohesion associated with sandstones, igneous and metamorphic rocks on steep slopes.

4.4.4 Sedimentation

Sedimentation is the settling out of soil particles from flowing water in a drain, stream, river or lake. For low Reynolds (R) numbers [$R = v.d/\nu < 0.1$], the velocity of fall is given by Stokes' Law:

$$v = [(gd^2)/18\nu]. [(\gamma_s - \gamma)/\gamma] \quad [9]$$

where:

v = fall velocity of the soil sphere (m/s)
g = acceleration due to gravity (m/s^2)
d = diameter of sphere of soil (m)
ν = kinematic viscosity of the fluid (kinematic viscosity of water at 20^{0}C is 1.01×10^{-6} m^2/s)
γ_s = the unit weight of the soil sphere (kN/m^3)
γ = the unit weight of water (10 kN/m^3)

Over the entire range of Reynolds numbers the fall velocity in terms of the drag coefficient C_d is given by Vanoni (1975):

$$v = \{[4/3] [(g. d)/C_d] [(\gamma_s - \gamma)/\gamma]\}^{0.5} \quad [10]$$

where:

C_d = the drag coefficient; other symbols as in [9]

Equation [10] can be solved by trial and error from curves of drag coefficient against Reynolds number or by a simple way provided in Vanoni (1975) in a nomogram. For example, quartz spheres 0.01, 0.1, 1.0 and 10 mm diameter have fall velocities of about 0.0001, 0.006, 0.15 and 0.74 m/sec respectively. In a sediment-laden water, interference between neighbouring particles tends to reduce their settling velocity.

4.4.4.1 Design of a sedimentation pond

In order to settle out discrete particles from overland flows, settling ponds should be constructed to settle out sediments before these flows enter any receiving waters such as rivers or streams. These ponds can be designed in accordance with engineering practice used in the wastewater treatment industry for the design of settlement tanks.

A loading rate of 10 m^3/m^2.day is suggested and should be verified in field trials. For a uniform overland flow of 1000 m^3/day from 10 ha, which would occur when rainfall is greater than 10 mm/day, the surface area of the settlement pond would be 100 m^2. This pond could have plan dimensions of 5 m wide by 20 m long. The depth should be greater than 2 m. The pond should be designed so that quiescent conditions exist in the settling zone and uniform flow occurs across its width. A stilling basin should be constructed at the entrance to the pond, possibly from timber poles arranged as in Figure 17.

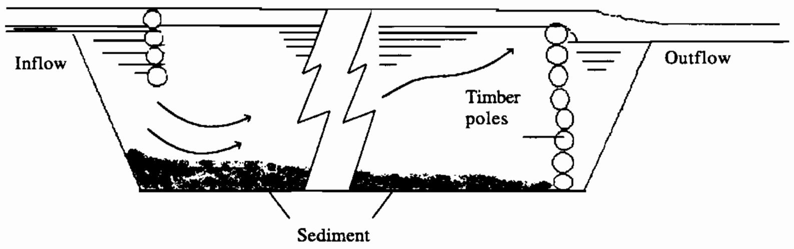


Figure 17: A typical sedimentation pond

The flow from the pond should be arranged so that the weir overflow rate is not high enough to cause particles which are settling to be pulled out of the pond. In the wastewater industry, a typical value of 200 m^3/day is used for a 1.0 metre length of weir. The basin length should be four times its width.

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