Field drainage for dry foot crops in the (semi-)humid tropics

L.K. Smedema

Euroconsult, Arnhem, The Netherlands

1 Introduction

The knowledge and application of field drainage is still very much limited to the developed countries in the temperate zones. In contrast, field drainage in the tropics is a neglected subject, both in terms of attention and research devoted to the subject, and in terms of tracts of land provided with proper field drainage systems (drainage for salinity control in the semi-arid tropics being the sole exception). This situation cannot be accounted for by a lack of need for drainage, as under the prevailing heavy rainfall conditions much land in the (semi-)humid tropics experiences serious waterlogging.

In addition to technical constraints (to be discussed below), the present state of field drainage in the tropics is of course also related to the overall state of development of the countries concerned, with as particular aspects:
- Low input/output type of agriculture limiting the economic scope for improved field drainage;
- Agricultural production often limited by a number of factors, field drainage not always being the minimum factor;
- Lack of institutions, trained personnel and funds for research, development and extension.

In this respect it is significant that the few cases of proper field drainage in the (semi-) humid tropics almost all relate to either a developed country (e.g. the southern part of the USA) or to estate-type agriculture in the developing countries (sugar estates in the Guyana's, banana estates in Central America, oil palm estates in Malaysia, etc.). Other high input/output types of agriculture in the (semi-)humid tropics are generally undertaken on the naturally better drained upland soils where intensive field drainage is not required. The local farmers will often also have adapted their land use to the prevailing conditions (rice and other tolerant crops on the bottom lands, other crops higher on the slopes) or have adopted 'ad hoc' measures to reduce waterlogging damage to crops (planting on mounds or raised beds, Figure 1). Regular field drainage systems are, however, almost non-existent.

This review paper is restricted to the field drainage of dry foot crops: drainage of wet rice has been dealt with in a separate paper (Bhuiyan and Undan 1986). A further restriction is that only waterlogging problems due to excess rainfall have been considered. Other drainage problems like flooding and erosion are of course also highly relevant to the tropics, but generally require other solutions.

Drawing attention to the neglected state of field drainage in the (semi-)humid tropics, would actually appear to come at an appropriate time. The agricultural develop-

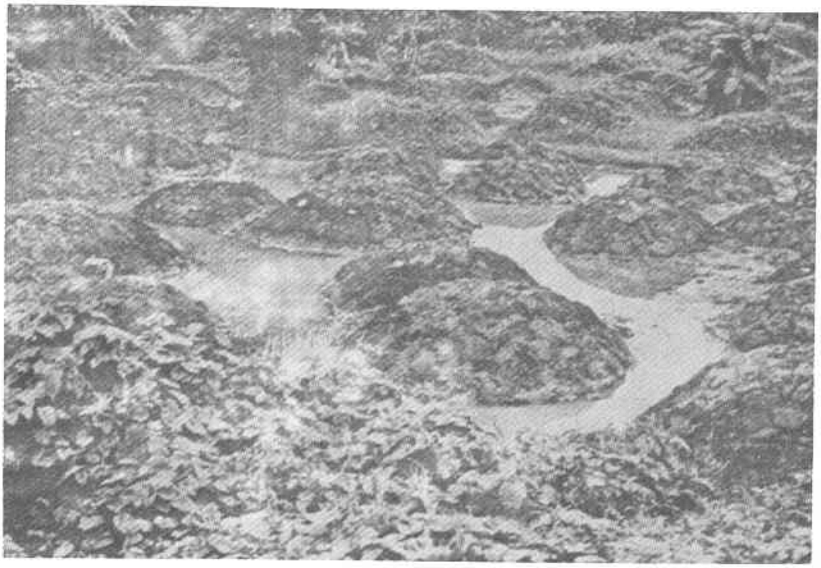

Figure 1 Growing of upland crops on mounds during the rainy season in Eastern Nigeria (Lal 1983)

ment in some countries in this region has reached a point where large-scale drainage improvement may have become viable and necessary, while other countries will sooner or later reach this stage. Some countries in the monsoon region of S.E. Asia have also reached self-sufficiency in rice production and are actively exploring possibilities for crop diversification. Improved drainage undoubtedly has an important role to play to create suitable conditions for the introduction of non-rice (dry foot) crops in the traditional low land rice growing areas.

2 The waterlogging problem

Waterlogging refers to a situation where (part of) the main rootzone receives excess water to the extent that it hinders the farming of the land. The adverse effects on farming may be grouped in two categories:

a. Impaired crop growth: the water and nutrient uptake functions of root systems are impaired by the poor aeration conditions in waterlogged soils. Especially the harmful effect of oxygen shortage in the rootzone is generally much more severe in warm than in cold climates (Figure 2), since in warm climates the soil oxygen is consumed more rapidly and the water uptake demands generally are higher (Williamson and Kriz 1970).

   In addition there are other harmful effects of waterlogging on crop growth (denitrification of the soil, formation of toxic substances, deterioration of soil structure, etc.). Some of which might also be strongly influenced by the soil temperature.

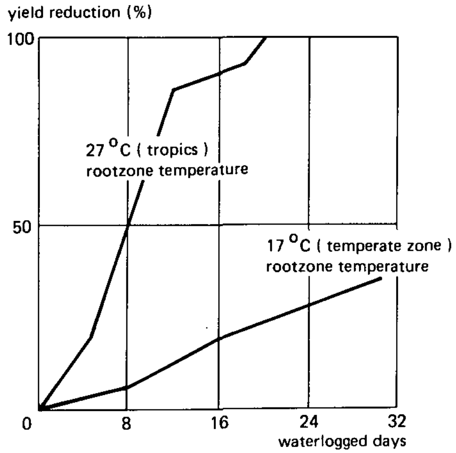

Figure 2 The defect of soil temperature on yield reduction of plums due to waterlogging (Row and Catlin 1971)

The damage varies greatly depending on such things as the type of crop, duration and frequency of waterlogging, and on its timing in relation to crop development. Even for the temperate zones where so much more research on drainage requirements has been done, very little 'hard' information is available on tolerances and damage due to waterlogging and on response due to improved waterlogging control. For tropical crops under field conditions, such information is virtually non-existent.

Waterlogging will not generally lead to harmful soil salinity levels in the humid tropics. In the semi-humid tropics, however, crop growth may be affected by poor aeration during the wet season and also by excess soil salinity during the dry season (Figure 3).

Such salinity problems may be expected when leaching conditions during the rainy season are unfavourable (e.g. due to poor percolation and drainage conditions of the soil), while on the other hand, conditions are favourable for a strong capillary salinization during the dry season (e.g. due to the occurrence of saline groundwater at shallow depth). Few such cases have been identified, while the identified cases generally seem to relate to situations with fossil salinity sources, either in the soil but more often in the groundwater. Introduction of irrigation during the dry season could in some cases upset the natural favourable salt balance in the semi-humid tropics when no drainage measures are taken, as has generally been the case with irrigation development in the semi-arid tropics.

b. Impaired farming operations: the reduced workability of the soils and the reduced accessibility of the land under waterlogged conditions will result in either delays, higher costs or poorer quality of work. The incurred damage is of course highly dependent on the prevailing farm system, especially on the degree of mechanization. In modern farming in the temperate zone, waterlogging often causes more damage due to its adverse effects on farming operations than due to its direct impact on crop growth. Under subsistence farming, the effects on farm operations would, however, be minimal, while climatic conditions in the tropics generally allow more flexibility in the timing of planting than in the temperate zone where especially spring planting is very critical. Future developments rather than present problems should be considered in this respect.

Adapting crop calendars to the prevailing climatic conditions, notably to avoid coincidence of critical crop growth or farm operation periods with high rainfall periods, may help to solve waterlogging problems. This approach, however, also has its limitations as temperature and sunshine may favour the growing of certain crops during certain seasons, while with rainfed agriculture the main crop season will naturally largely coincide with the main rainy season.

The role of the evapotranspiration should also be mentioned in this respect: the year-round high evaporative demand of the atmosphere makes evapotranspiration a major water-depleting mechanism of tropical land. The concept of self-drainage ('crops drinking their way out of a waterlogged situation') is appealing but also deceptive as growth conditions are obviously not optimal during such a self-drainage period. Moreover, the strongly drying atmospheric conditions which enhance self-drainage also inflict the most crop damage as under waterlogged conditions the root system will be unable to meet the high evapotranspirative demand. However, in combination

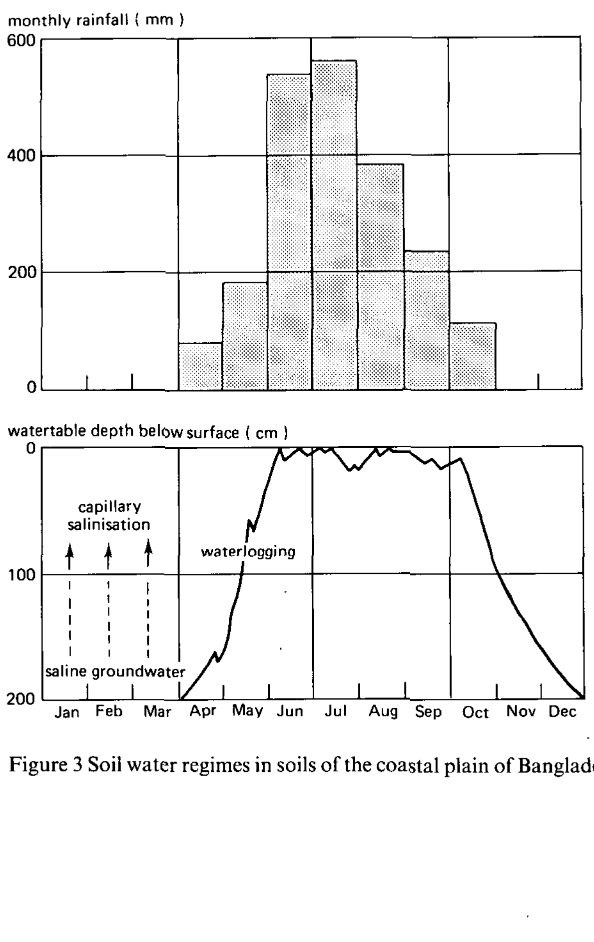

Figure 3 Soil water regimes in soils of the coastal plain of Bangladesh

with improved drainage, evapotranspiration can be a powerful aid to shorten excess water periods and also to create a reserve storage in the soil during intervening dry periods which can accommodate (part of) subsequent storms. This especially applies to soils with poor internal drainage characteristics (e.g. the so-called 'heavy lands'), where the high tropical evapotranspiration rates (easily 5-7 mm/day) are in fact often of the same order as the 'through the soil' drainage rates.

3 Types of drainage flow

Excess water on the land or in the soil may be drained from the land/soil by movement of the water to a nearby drain by one of the following three flow types (Figure 4):

- Overland flow (surface run-off): flow of non-infiltrated surface water over the surface of the land;
- Interflow: lateral flow of perched/impeded soil water through the soil over an impeding layer;
- Groundwater flow: flow through the soil below the true watertable.

Overland flow and interflow are difficult to identify separately, and often occur simultaneously. Drainage systems functioning on the basis of these two types of flow remove excess water mostly from the surface of the land and from the permeable topsoil, and are therefore termed shallow drainage systems (Smedema and Rycroft 1983). Groundwater drainage systems function on the basis of groundwater flow. The aim of groundwater drainage systems is to maintain a deep watertable enabling/promoting excess water to percolate down through the soil profile to the subsoil/substratum where it is picked up by the drains. Groundwater systems can only be used effectively and economically when the percolation flow is not impeded, and when there are good conditions in the subsoil/substratum for groundwater flow to the drains.

The prevailing type of drainage flow depends especially on the rainfall intensity in relation to the rate at which water can move downward through the soil profile. Under sustained excess rainfall, this downward water movement proceeds under approximately unit gradient (gravity flow), and the maximum steady percolation rate may therefore just equal the (vertical) hydraulic conductivity (K) of the relevant profile layer(s). When the rainfall rate $P > K$ of the subsoil, a perched watertable builds

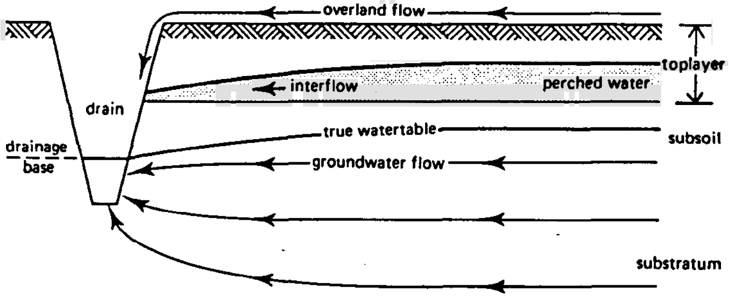

Figure 4 Types of field drainage flow

up in the topsoil, leading to interflow when a lateral gradient is imposed on this water. When $P > K$ of the topsoil, water will pond on the land surface and overland flow may occur.

During prolonged heavy rainfall, the entire soil profile may become saturated, raising the watertable to the soil surface. In view of the higher rainfall depths and intensities, situations conditional to the occurrence of interflow and overland flow may be expected to be much more prevalent in the tropics than in temperate zones. Soils which may have adequate infiltration/percolation capacity to be suitably drained 'through the soil' with groundwater drainage systems under temperate zone conditions, may be more suitably drained by shallow drainage systems under tropical conditions. In this connection, the role of interflow should especially be stressed. This type of flow is now widely accepted by hydrologists as a major drainage flow mechanism in soils (Ward 1984), but drainage engineers do not seem to have yet fully grasped the significance of this type of flow for field drainage, especially in the tropics.

4 Field drainage methods/systems

Figure 5 presents the main characteristics of the more widely-used field-drainage methods of the (semi-)humid tropics. It is notable that all these methods are essentially based on combinations of induced overland flow and interflow, rather than on induced groundwater flow. In upland situations, natural groundwater drainage flow may be adequate to maintain low groundwater tables, but this is not the reason for the absence of groundwater drainage systems in lowland situations. A further analysis of the role of groundwater drainage systems in the (semi-)humid tropics has been presented in section 5 of this paper.

The most common field-drainage method of the (semi-)humid tropics is the bedding system. This method is of course also known in the temperate zone, although mostly restricted to flat heavy land. The method essentially involves the provision of closely-spaced shallow drains to induce overland flow and interflow. The drain depth is often not more than 30 cm. The spacing may be only a few metres as in some indigeneous systems ('raised mounds' in West Africa, the 'sorjan' system of S.E. Asia), and in the modernized versions suitable for mechanized farming (the 'Louisiana bank' system developed for sugar cane in the Mississippi delta and the 'broad bed' system developed by ICRISAT). Close spacings provide steeper gradients for drainage flow from the beds to the drains and more in-field storage of excess water. Crowning of the beds also enhances the drainage flow from the beds by providing steeper gradients, allowing wider spacing than with flat beds for the same drainage rates.

The parallel shallow ditch system of field drainage is generally applied where conditions for discharge somewhat deeper through the soil are more favourable (e.g. less rainfall, deeper and more permeable soils). The drains are deeper than with the bedding system and induce some (shallow) groundwater drainage in addition to inducing overland flow and interflow.

As an additional drainage measure, crops in the (semi-)humid tropics are often grown on ridges which provide 'dry feet' to the crops while the furrows between these ridges provide means of conveyance for overland flow (row drainage), as well as means for in-field storage of excess rainwater. When the ridges are aligned in parallel with the field drains (as in Figure 5), the direct lateral overland flow to the drains is blocked, and cross drains (variously termed ridge cuts or quarter drains) should be installed to intercept the row drainage at suitable intervals and lead it to the field drains. The alternative alignment with ridges/furrows perpendicular to the field drains, is detrimental to farm operations when the field drains are closely spaced and are well incised, while the field drains are made more shallow and passable, or the spaces between the drains are widened. These will generally be at the expense of the quality of the drainage achieved.

Land grading has been applied on a large scale, especially in the USA, as a measure to promote overland drainage while reducing the intensity of the in-field drain systems, thus facilitating mechanized farming. As such it has also been introduced on some tropical sugar estates (Smith 1976). However, it is doubtful whether this is a generally recommendable practice for the (semi-)humid tropics, even when the consideration is not included that the present state of mechanization does not generally pose a high enough demand on sizes and shapes of field plots. Elimination of field drains results in more prolonged saturation of topsoils after rain, as the interflow drainage of the topsoil is reduced and not fully compensated by improved overland drainage. Furthermore, the combination of enhanced overland flow and reduced in-field storage due to filling-in of field drains, may lead to serious downstream flooding problems or

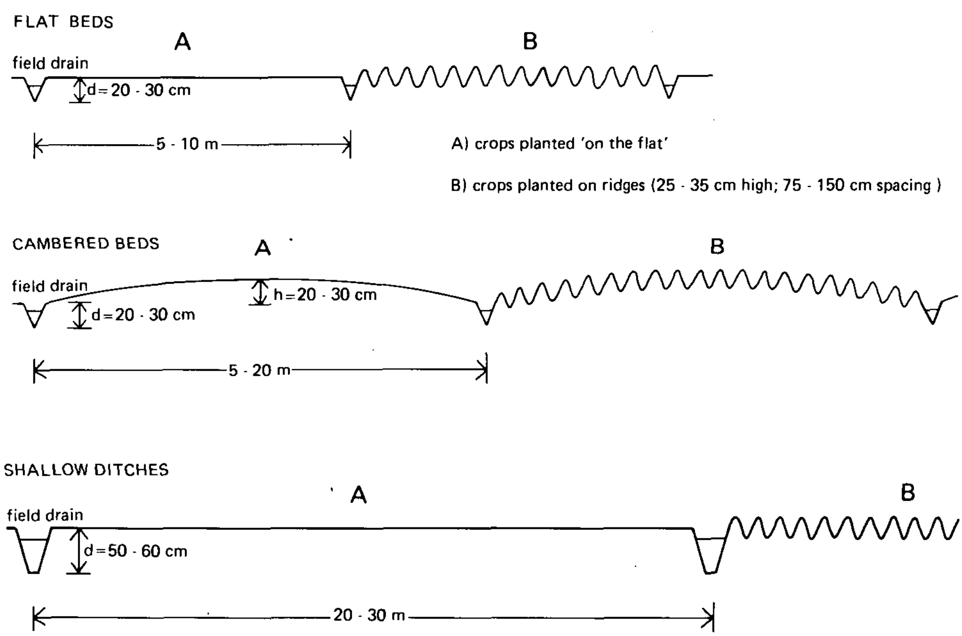

Figure 5 Field drainage systems of the (semi-)humid tropics

require large main-system capacities. The topsoil drainage function by interflow inducement of the field drains and the in-field storage function of these drains, should be duly recognized and for as yet large-scale land grading would seem to find limited application in (semi-)humid tropics. Small-scale grading and smoothing of the land is, however, useful, as it helps to spread the infiltration load equally over the surface of the land, and prevents excessive and prolonged ponding.

Table 1 Calculation of common* drainage loads for the temperate zone and for the (semi-)humid tropics

Duration (days)	Rainfall (mm)	Deductions		Drainage load	
		Storage (mm)**	Evapotranspiration (mm)***	Total depth (mm)	Rate (mm/day)
Temperate zone (The Netherlands)					
1 (24 hrs)	15– 25	15	–	0– 10	0–10
2	25– 35	15	–	10– 20	5–10
3	35– 50	15	2	18– 33	6–11
5	45– 60	15	5	25– 40	5– 8
10	70– 90	15	10	45– 65	4– 7
30	80–110	15	30	35– 65	1– 2
(Semi-) humid tropics					
1 (24 hrs)	60– 90	20	–	40– 70	40–70
2	80–120	20	–	60–100	30–50
3	100–150	20	5	75–125	25–40
5	120–200	20	10	90–170	20–35
10	170–300	20	25	125–255	12–25
30	300–400	20	75	205–305	7–10

* 1 to 2 times occurrence per season/annum
** 5-10 mm storage in the soil profile; 5-10 mm storage on the soil surface } giving a total storage between 15-20 mm
*** temperate zone : 1 mm/day; (semi-)humid tropics: 2-3 mm day } both values for periods > 2 days

5 Drainage rates versus discharge capacities

In Table 1 common drainage loads i.e. excess water quantities occurring one to two times per season/annum have been calculated by deducting expected rainfall depths by storage and evapotranspiration. These calculations apply to an assumed critical situation during the wet season in which antecedent rain has replenished all exhausted storage, and only a small deduction can be made for the dynamic storage (water temporarily stored to build up the necessary head and gradients for drainage discharge). Deduction for evapotranspiration losses have been applied only for rainfall periods longer than 2 days (for shorter periods these losses are insignificant in relation to the rainfall depths, while these have already been largely accounted for in the measured rainfall depths).

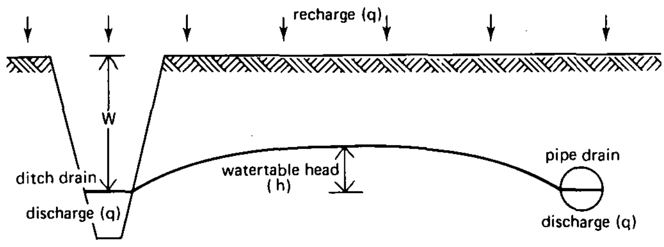

Figure 6 Illustration of the q and h parameters of groundwater drainage systems

In Table 2 the calculated drainage loads have been compared with what is considered to be the economically feasible maximum groundwater drainage capacity. This capacity was deduced from applied drainage intensity values (q/h ratio, Figure 6). Systems with a high q/h ratio give better watertable control, but are also more costly as spacings must be narrower. For North West Europe, applied q/h ratio's vary from $q/h = 0.010$ day^{-1} for tolerant/low value crops, to $q/h = 0.015$ day^{-1} for sensitive/high value crops. These values apply to systems with a drain depth $W = 1.0\text{-}1.2$ m. The maximum discharge capacity of these systems, applying when the watertable is near the soil surface (say $h = 1.0$ m), amounts to:

$$q_{max} = (q/h) * h_{max} = 0.010-0.015 \text{ m/day} = 10-15 \text{ mm/day}$$

Very little information is available on economically feasible drainage intensity limits of groundwater drainage systems in the (semi-)humid tropics, but values proposed by Carter (1976) for sugar cane in the Mississippi area are of the same order as those used in North West Europe. The economic limit to groundwater drainage capacity, both for the temperate zone and for the (semi-)humid tropical conditions, would therefore appear to be in the order of 10-15 mm/day.

Comparing this capacity with the discharge requirements (Table 2) calculated earlier, the limitations of groundwater drainage under (semi-)humid tropical conditions are clearly demonstrated. Such systems cannot prevent waterlogging of the entire soil profile for periods of up to 10 days, while watertables remain near the topsoil for periods as long as 30 days. The temperate zone situation has also been presented in Table 2 for comparison, showing that waterlogging can generally be suitably controlled by means of groundwater drainage systems. This analysis is supported by available watertable regime studies.

6 Research and development

Research and development of drainage in the (semi-)humid tropics has thus far been very incidental and focused on cash crops grown on estates. The latter primarily applies to the sugar cane industry, much of which is located in (semi-)humid tropical lowlands. Long-term research on the drainage of sugar cane has been conducted at the agricultur-

Table 2 Comparison of prevailing types of drainage discharge in the temperate zone and in the (semi-)humid tropics

Drainage loads (1 to 2 events/season)		Types of drainage discharge		
Period (days)	Rate (mm/day)	Groundwater drainage	Interflow drainage	Overland drainage
Temperate zone (The Netherlands)				
1	0–10	++	−(+)	−
2	5–10	++	−(+)	−
3	6–11	++	−(+)	−
5	5– 8	++	−(+)	−
10	4– 7	++	−(+)	−
30	1– 2	++	−(+)	−
(Semi-) humid tropics				
1	40–70	+	+	++
2	30–50	+	+	++
3	25–40	+	+(++)	+
5	20–35	+	+(++)	+
10	12–25	++	+(++)	+
30	7-10	++	−(+)	−

++ sole or major type of drainage discharge
+ additional type of drainage discharge
− not normally occurring/required
( ) applies to drainage of heavy land

al experimental station at Baton Rouge (Louisiana, USA). The past research concentrated on the improvement of shallow drainage systems (improved bedding systems, land grading) but recently some experiments with groundwater drainage by means of pipe systems have also been initiated (Carter 1976 and Carter et al. 1982). Although good results were obtained, the economics of pipe drainage for sugar cane appears to be highly unpredictable due to the instability of the world sugar market. Moreover, rainfall conditions in the Mississippi area are moderate (reasonably distributed annual rainfall of some 1300 mm) compared to other (semi-)humid tropical locations, and the scope for groundwater control might be rather favourable. Good response to improved groundwater drainage was, however, also obtained with sugar cane in North Queensland (Australia) where the annual rainfall is as high as 2000-4000 mm, mostly concentrated in the summer (November-April).

Banana yields have also been found to respond rather well to improved groundwater drainage under (semi-)humid conditions (reports by Kamerling 1974 from Surinam, and by Murillo 1986 from Costa Rica). Both countries are located in the humid tropical zone of the Caribbean, characterized by pronounced and prolonged wet seasons. In Surinam (annual rainfall some 2000 mm), ditches are still exclusively used, but in Costa Rica (annual rainfall 2000-3000 mm) pipe drainage has recently been introduced in some banana estates.

Oil palm estates in the coastal zone of Malaysia (monsoon rainfall of 1550-2500 mm) still seem to rely entirely on shallow drainage systems; up until now no work on deep groundwater drainage systems has been undertaken (Hubbard 1975).

The lack of systematic drainage research and development is even more apparent for food crops grown by peasant farmers. The recommended drainage solutions must obviously be compatible with the farming systems practised, which are quite different from farming systems of the modern agriculture of the temperate zone and of the estate-type agriculture of the tropics. Instead of the familiar modern technological solutions as land grading, pipe drainage etc., intermediate technology solutions may be more appropriate (see the approach to the development of land and water management technologies outlined by Kortenhorst 1985). Some work on the plant physiological drainage requirements of tropical food crops has been done at the IITA (Ibadan, Nigeria), but the technological, socio-economical and institutional aspects of improved drainage for peasant farming in the (semi-)humid tropics, have as yet hardly been touched upon by the relevant national and international agricultural research stations.

7 Discussion and conclusion

Modern land drainage has its roots in the agriculture of the temperate climates of North West Europe and the USA. Here it has reached a firm scientific basis as a field of applied soil physics and applied hydrology. Significant changes have taken place in the past two decades, notably:

- A shift in objectives from increased crop production to improve conditions for (mechanized) farm operations and conservation of the environmental quality;
- The introduction of new technology (different types of drainage machinery and drainage materials).

Around 1960-1970, land drainage extended from the temperate zones to the semi-arid tropical zones, where basically the same land drainage methods were applied to control soil salinity. In tandem with this development, land drainage also extended from the developed world to the developing world. While the first extension introduced new technical concepts, the second extension was even more significant in placing land drainage in an entirely different socio-economical and institutional situation.

It would appear that a new challenge has since arisen on the horizon, i.e. the extension of land drainage to the (semi-)humid tropics to support general agricultural development in this region, and in particular crop diversification in traditional rice -growing areas. This may require the development of new drainage methods and technologies adapted to the prevailing soil and water conditions and to the farming systems of the subsistence farmer.

In the discussion of the drainage conditions and drainage requirements of the (semi-) humid tropics presented in this review paper, some significant differences from the temperate zone drainage situation emerged. These are mostly the result of the much higher rainfall load to be coped with in the (semi-)humid tropics, which is often so enormous that waterlogging of the entire rootzone must be accepted. Under these conditions, shallow drainage systems which promote interflow and overland flow drainage can play an important role. Groundwater drainage induced by deeper drains, however, also appears to be effective, and the ideal field drainage systems for the (semi-) humid tropics may in fact have to provide three functions:

- Overland drainage to serve as a main discharge process during short periods (< 2 days) of very high and very intensive rainfall when the 'through the soil' discharge capacity (combined interflow and groundwater flow) or the infiltration capacity of the soil is inadequate, resulting in ponding of excess rainwater on the soil surface;
- Interflow drainage to serve as the main discharge process during rather prolonged (2-5 days) periods of heavy rainfall when either watertables have risen to near the soil surface or when perched watertables have built up in the toplayers of the soil profile due to the high recharges;
- Groundwater drainage to achieve a rapid watertable drawdown during intermittent rainless periods during the rainy season, to restore aeration of the upper rootzone. To lower the watertable during prolonged dry periods even deeper, after the end of the rainy season, the self-drainage (evaporative soil water depletion) of the soil can be relied upon.

To achieve the groundwater drainage objectives, a reasonably deep and narrowly-spaced system of drains is required. The interflow drainage also requires a rather narrow drain spacing, but here the drainage base can be quite shallow (30 cm depth just below the permeable topsoil will suffice). A shallow drainage base will also suffice for overland drainage but depending on the lay-out of the land and the secondary drainage measures taken (row drainage, grading, smoothing), the spacing of the field drains may be rather wide. Separate field drainage systems could of course be used for the three types of drainage flow, but this would seldom be a viable solution. When the drain functions are combined, the demands imposed by groundwater drainage on drain depth and drain spacing will usually prevail, while the type of field drain must meet the shallow drainage flow requirements (should be an open drain, e.g. a ditch, although a highly permeable, e.g. gravel-filled trench, could be considered when there is only interflow). Up to now no field drainage systems have been developed which fulfil all these requirements and functions whilst remaining economically feasible and compatible with such other requirements as rational plot lay-out, easy field accessibility, efficient field operations, low land loss and low maintenance requirements.

Other differences from temperate zone drainage and special features of drainage in the (semi-)humid tropics may be noted:

- Responses to improved drainage: whereas in the temperate zone and in the semi-arid tropical zone these responses mainly relate to farm operations and salinity control respectively, responses to improved drainage in the (semi-)humid tropics primarily relate to crop growth. Considerable yield responses may in fact be expected due to the prevailing high soil temperatures;
- Adapted farming: given the technical difficulties of adequate waterlogging control, some form of adapted farming is often a sensible contribution to a drainage solution. The classical example is of course the use of the lowlands for wet rice land (the tropical parallel of grassland use in the temperate zone). Other examples are the use of tolerant crops/varieties and scheduling of crop calendars to circumvent criti-

cal situations. While adapted farming may offer the best available solution in some cases (e.g. for poorly drainable land), it may impose undesirable and unnecessary constraints which could be more suitably solved by improved drainage in other cases;

- Secondary drainage measures: special farming and cultivation practices as an aid to improved drainage, will always play an important role in the (semi-)humid tropics. Several of these measures have already been mentioned: ridge cropping, smoothing and grading of the land surface. For interflow drainage, good soil management to maintain a permeable topsoil is important, while this is also true for soil conservation measures with respect to overland flow;
- Storage function of field drains: field drains in the (semi-)humid tropics have to fulfil several functions. Firstly the classical 'sink' function (point/line of low hydraulic potential, attracting a flow of excess water from the surrounding soil/land). In addition, however, it is often desirable that the field drains also fulfil a combination of significant storage functions. This combination of functions poses requirements as to the type of field drain, the spacing/intensity and the lay-out;
- Attention and maintenance: field drainage systems involving interflow and overland flow will always require much care to ensure their proper functioning throughout the drainage season. This is inherent to the 'open/surface' nature of these systems which makes them more prone to flow blockage than e.g. underground pipe drainage systems which can function, once properly installed, with a minimum of care and maintenance. It is also true that much of this care has to be done in a standing crop and can only suitably be realized by hand labour.

Finally attention is drawn to the fact that at present in many of the countries concerned, main drain systems are in a deplorable state due to both lack of funds and lack of proper institutional arrangements. Under these conditions improved field drainage must obviously go hand in hand with improvement of the main drain systems.

References

Bhuiyan, S.I. and R.C. Undan 1986. Drainage in rice culture in the Asian humid tropics. Paper presented at this symposium.

Carter, C.E. 1976. Drainage parameters for sugar cane in Louisiana. Proc. 3rd National Drainage Symposium, ASAE.

Carter, C.E., V. McDaniel, and R.L. Bengtson 1982. Potential for subsurface drainage in the Lower Mississippi Valley. Proc. 4th National Drainage Symposium, ASAE.

Hubbard, F.T.P. 1975. Drainage of coastal clay soils. Planter (Malaysia) 54: 708-717.

Kamerling, G.E. 1974. Soil-physical and agro-hydrological research into the Quaternary coastal plain of Surinam. PUDOC Wageningen, The Netherlands (in Dutch).

Kortenhorst, L.F. 1985. Irrigation lessons from indigenous farming. In: Traditional Irrigation Schemes and Potentials for Improvement. Ed. J.F. Mock, Bulletin 9, DVWK.

Lal, R. 1983. No-till farming: Soil and Water Conservation and Management in the Humid and Subhumid Tropics. Monograph 2, IITA.

Murillo, J.L. 1986. Land drainage in the Atlantic region of Costa Rica. Paper presented at this symposium.

Row, R.N. and P.B. Catlin 1971. Differential sensitivity to waterlogging and cyanogenesis of peach, apricot and plums. J. Am. Soc. Hort. Sc. 96: 305-308.

Smedema, L.K. and D.W. Rycroft 1983. Land Drainage. Batsford, London.
Smith, W. 1976. Aspects of drainage related to cultivation and harvesting of sugar cane. Proc. 3rd National Drainage Symposium, ASAE.
Williamson, R.E. and G.J. Kriz 1970. Response of agricultural crops to flooding, depth of watertable and soil gaseous composition. Transactions ASAE 13: 216-220.
Ward, R.C. 1984. On the response to precipitation of head streams in humid areas. J. of Hydrology 74: 171-189.