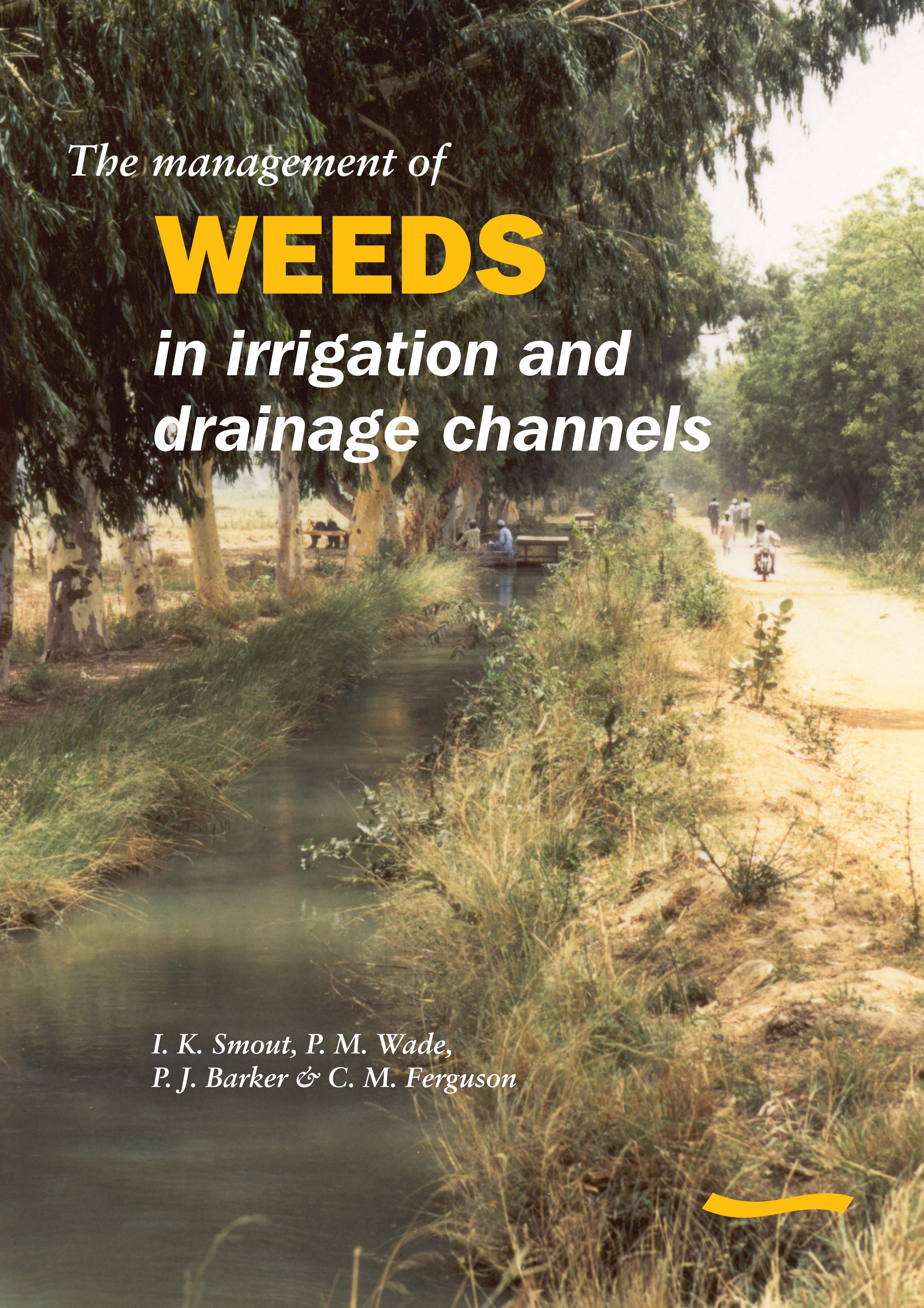

The management of WEEDS in irrigation and drainage channels

I. K. Smout, P. M. Wade, P. J. Barker & C. M. Ferguson

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CHAPTER 1

INTRODUCTION

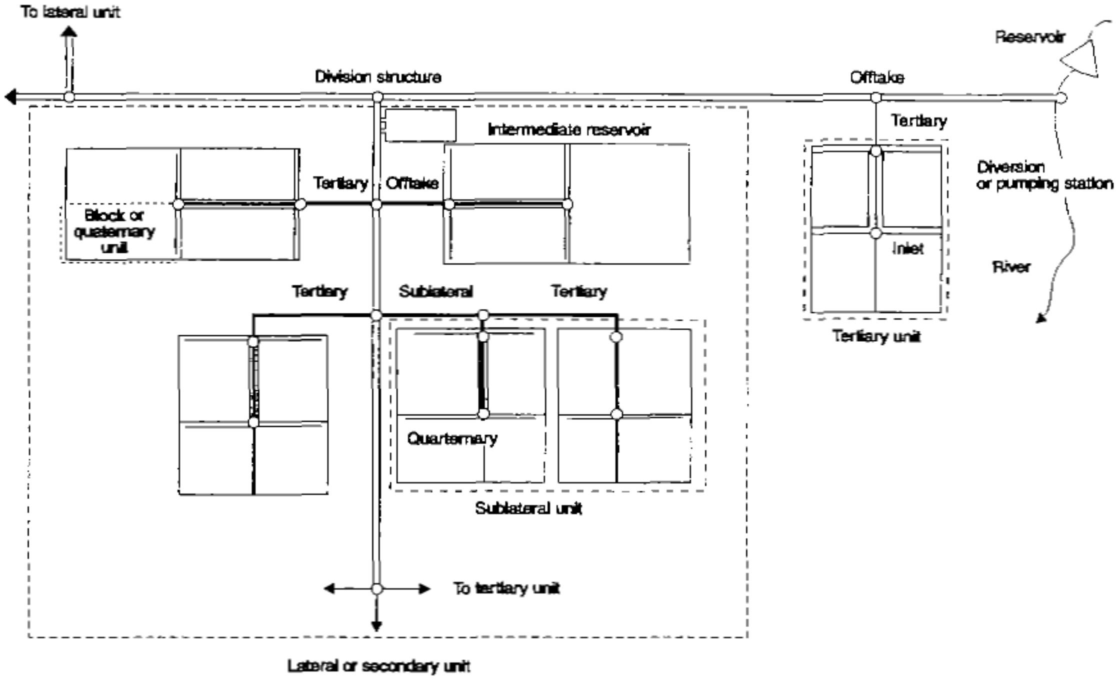
1.1 Introduction

The standard of maintenance of irrigation and drainage is poor in many irrigation systems throughout the world. Inferior management of those weeds growing in the channel, aquatic weeds leads to a number of economic, social and environmental problems:

1. Aquatic weeds decrease flow velocities and cause reduced discharge capacity and increased siltation, leading to losses of farm production and agricultural land, by:
   - shortages of irrigation water, especially at the tail of canals
   - waterlogging from poorly performing drains.
2. Weeds provide a habitat for vectors of disease (such as schistosomiasis and malaria) and other pests (for example, rats and snakes) affecting human health and crop production.
3. Weeds may spread from the canal into irrigated fields, reducing crop yields.
4. Inefficient weed control causes wastage of scarce resources and environmental damage:
   - unproductive inputs in existing maintenance work including labour, machinery and chemicals
   - foregone outputs leading to low crop production
   - health hazards to workers and farmers from herbicides and schistosomiasis.
5. A vicious circle develops of poor water supply, poor agricultural productivity, farmers' reluctance to pay water charges and underfunding of maintenance, further weakening infrastructure and management
6. There is a failure to realise the potential uses of weeds, for example as manures, feedstuffs and building materials.

In this book we address these problems and seek to develop a new conceptual approach to the systematic management of aquatic and bankside weeds, based on interdisciplinary research which combines ecological, engineering, institutional and economic perspectives.

Management is used both in the technical sense of weed control, and in the institutional sense of managing operations. The two meanings are combined in the concept of weed management as a service which is provided (usually by an irrigation agency to farmers and the wider society) to control weeds within the irrigation and drainage system This includes canals and drains of all types and sizes, and intermediate or night storage reservoirs, but not the fields served by the system.



Source: Adapted from Bos (1985)

Figure 1.1. The hierarchy of irrigation and drainage channels: primary, secondary, tertiary and quaternary canals and drains

We can then consider ways to improve the effectiveness of the service, following the approach of Murray-Rust and Snellen (1993), in terms of:

- the degree to which the service meets the need for weed control (the level of service);
- the efficiency with which the organisation uses resources in meeting these needs.

As explained later in this chapter, the level of service includes both hydraulic and environmental criteria. Resources include water, finance, machinery and labour.

The book focuses on irrigation systems within tropical and sub-tropical areas and is based in large measure on experiences gained through work in Africa which is described in Chapter 2. The problems caused by weeds in irrigation and drainage channels are described in Chapter 3, and guidelines on the identification of feasible control options are presented in Chapter 4.

The next three chapters cover the selection of an appropriate control programme. Chapter 5 provides guidance on the setting of maintenance policy, Chapter 6 covers the methods of preparing a maintenance programme. Chapter 7 shows how economic tools can be used to select an efficient option, and in Chapter 8 we consider the incorporation of the weed control programme within an irrigation management programme.

Chapter 9 deals with the institutional aspects of management and the conclusions are presented in Chapter 10.

1.2 Types of irrigation system

This book is concerned with irrigation and drainage systems which use open channels for delivery of irrigation water and/or for removal of drainage water. Examples of these channels are shown in Plate 1.1. Most surface irrigation systems come into this category (though some use pipelines instead of open channels for irrigation or drainage), and it includes the open channel systems associated with some sprinkler irrigation and micro-irrigation (trickle) systems.

Irrigation and drainage channels are commonly described using the hierarchy: primary, secondary, tertiary and quaternary canals and drains, as shown in Figure 1.1.

Also included in this study are intermediate reservoirs (or night storage reservoirs) (Plate 1.2) which are placed within the canal system to provide operational flexibility. The intermediate reservoir is supplied at a steady rate from the upstream canal system, but then delivers water to users on a more convenient schedule or demand basis. Night storage reservoirs are a particularly common type of intermediate reservoir, which is filled on a continuous basis (day and night) from upstream, but delivers water during the day only.

1.3 Recent trends in irrigation development

There was a major expansion of world-wide irrigated area in the 1960s and 1970s, with the construction of new irrigation schemes supported by major funding agencies.

Conditions for new irrigation projects however have been seen as less favourable since the mid 1970s because of concern about FAO (1993):

- increased construction costs compared to falling crop prices (especially of cereals);
- environmental and social impact of irrigation and water resource development projects;
- disappointing performance of many irrigation projects, because of poor scheme conception, inadequate construction and implementation or ineffective management.

With a shift in aid agencies' priorities, governments have come under international pressure to reduce irrigation expenditure which, as a major part of government agriculture budgets, has become seen as a drain on public funds. Past borrowing for irrigation has also contributed to high levels of national debt, with costly servicing requirements.

Food and Agriculture Organisation (FAO 1993) refers to a shift from a 'supply-side management' of irrigation to a 'demand-side management' strategy, with a reduction of the role of government and an increased role for users. To provide a new institutional framework for the changed strategy, irrigation projects and programmes have included the creation and strengthening of water user associations (WUAs) and the turnover of management responsibilities to WUAs or private companies. There are limits, however, to the financial and technical responsibilities which rural communities in low-income countries can undertake satisfactorily. It is interesting to compare WUAs with agricultural input supply and marketing cooperatives. These have had a mixed record which has led to a poor reputation for WUAs and a reduced role in agricultural development in many countries.

A review of devolution of management in public irrigation systems in the mid-1990s found positive and encouraging experiences in Chile, Mexico, China, Columbia, Nepal and Indonesia, but stressed the need for development of a service culture in irrigation agencies, which is not necessarily easier to achieve by privatisation than by public sector management reform (Turral 1995). Another interesting finding was that:

"Evidence in the USA, Australia, the Philippines and other countries is starting to indicate that farmers may not necessarily be better managers than the state, particularly with respect to maintaining and financing repairs to the physical infrastructure. Desire for the minimum possible water price seems to neglect longer-term considerations or implicitly assumes that the government will always step in to finance deferred maintenance."

The turnover of schemes to local communities and privatisation do not remove the need for efficient and effective management of weeds in irrigation and drainage channels. Perhaps turnover and privatisation are better regarded as possible changes or threats to existing irrigation agencies which might encourage managers and technical staff to improve their own practice.

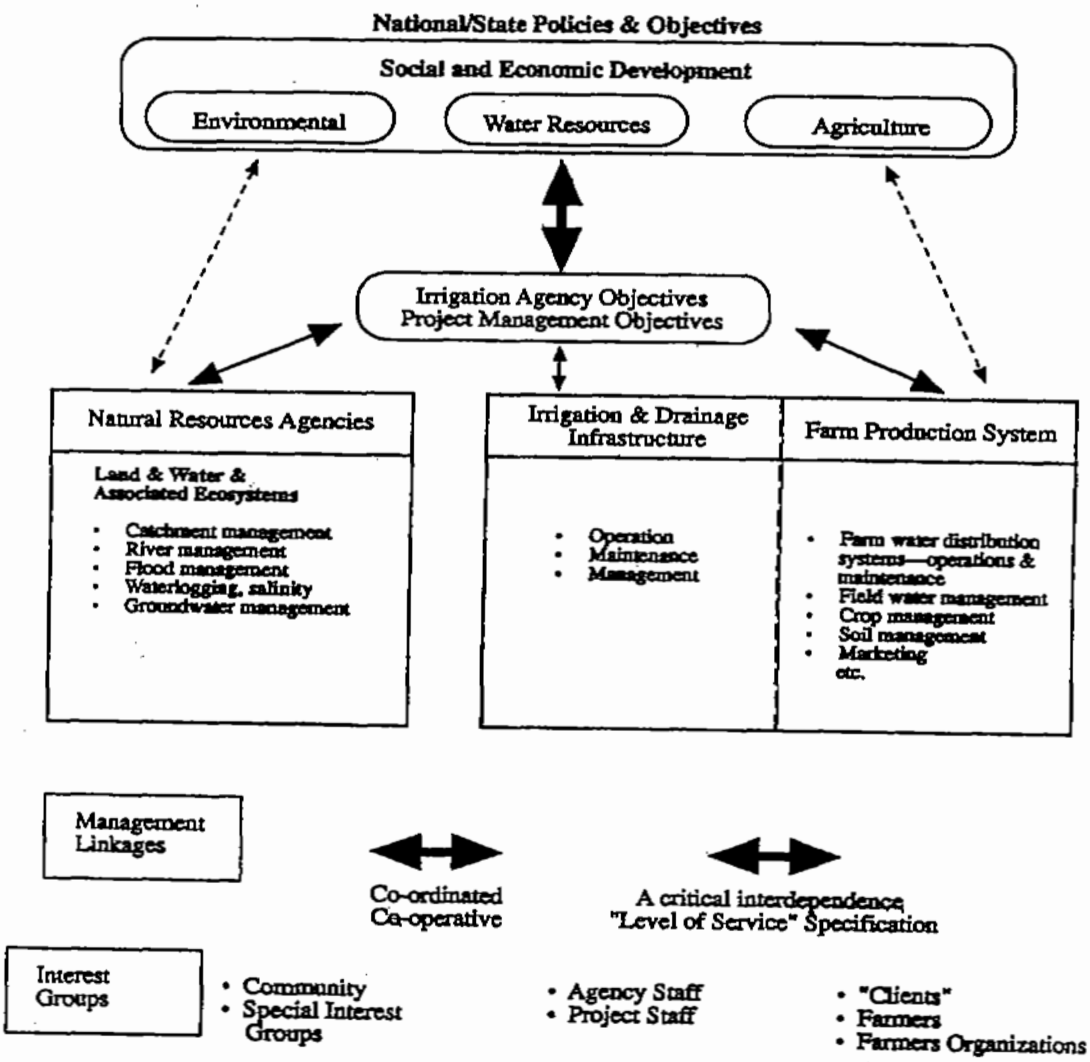


Figure 1.2. Sustainable development and management: management linkages

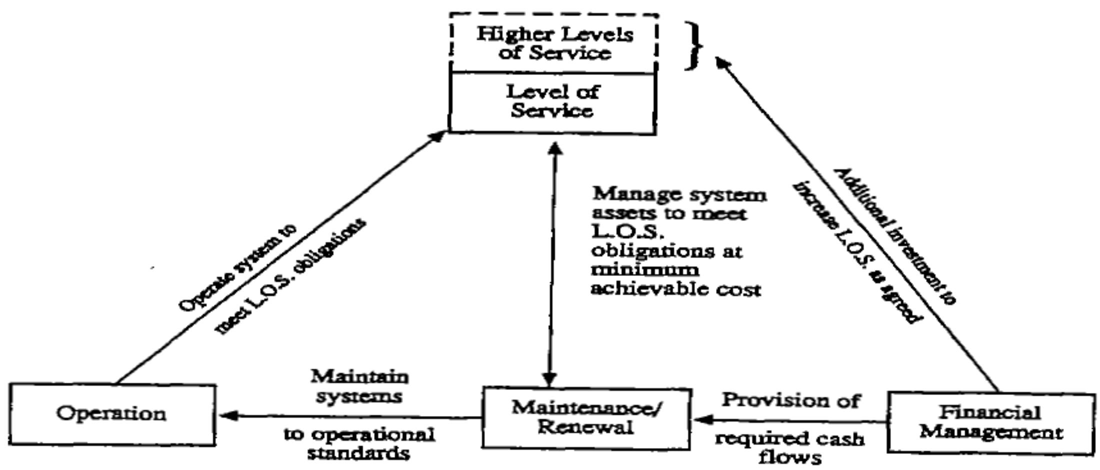
1.4 Irrigation management issues and approaches

During the 1980s and 1990s, widespread concern about poor irrigation management has been supported by detailed research. (An early example of this is a study for the World Bank by Bottrall (1981)). A comprehensive analysis from south Asia (Chambers (1988), stressed the need for an interdisciplinary "whole systems" approach including physical, bio-economic, human and environmental domains, and both space and time dimensions (Chambers 1988). It also identified five major blind spots or gaps in previous work, which helped explain past poor performance and provided the key to improved canal irrigation management:

1. main system management (the central gap)
2. canal irrigation at night
3. farmers' actions above the outlet
4. managers and motivation
5. methods and approaches for diagnostic analysis.

Subsequent research has addressed some of these issues, and we hope that this book will itself throw some light on the first and last blind spots.

Business management approaches have also been applied to irrigation systems in recent years, as to other public services, considering for example performance assessment (e.g. work by Small and Svendsen (1992) and Murray-Rust and Snellen (1993)) and strategic business planning (e.g. an ODA research project on Asset Management Procedures for Irrigation Schemes by IIS (1994)). A common finding is that these approaches require data which have not been collected routinely in the past. One of the challenges we face in writing this book is to develop procedures which are feasible for irrigation managers to introduce and sustain.



Notes:

1. For a specific Level of Service (L.O.S.), there will be an associated identifiable cost.
2. In poorly managed systems, improvements in L.O.S. can be achieved by improving management processes and control (often by some additional costs and by re-ordering financial priorities).
3. In well-managed systems, substantial increase in L.O.S. will generally require significant additional investment.

Figure 1.3. System management objectives

This challenge is being considered by the International Commission on Irrigation and Drainage (Constable 1993), which drafted the management context of irrigation and the objectives of irrigation system management (Figure 1.2 and 1.3). The concept of a Level of Service is used, representing a specific set of objectives chosen for the circumstances. The term Standard of Service is a similar concept used by the UK water industry, including by the Environment Agency for management of drainage channels (Birks *et al.* undated).

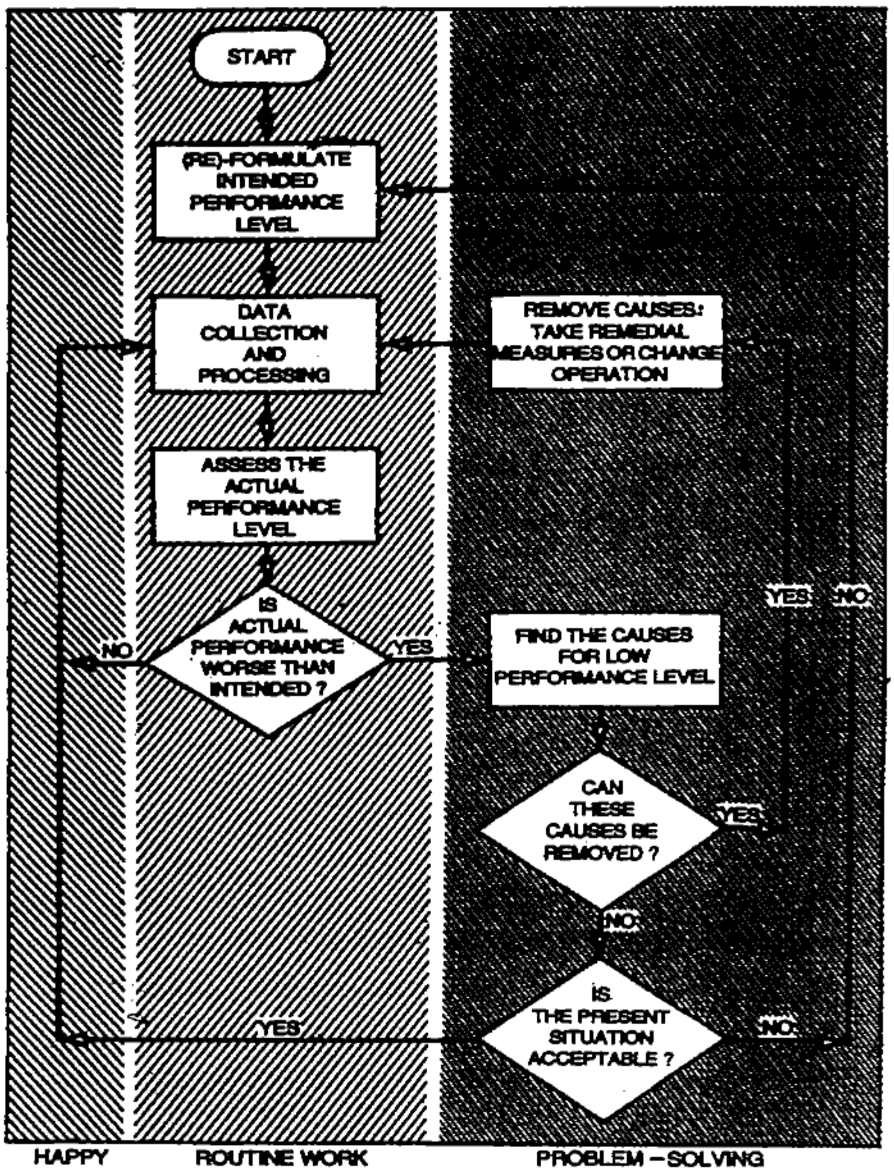


Figure 1.4. A simple flow chart of irrigation water management

The approach developed below considers an appropriate level of service which would be followed in planning maintenance work for irrigation and drainage channels, specifically weed management. This level of service would combine such factors as hydraulic performance, reliability/risk, cost effectiveness from financial and economic perspectives, and environmental and social impacts.

Wolters and Bos (199) provide a simple flow chart of the management process (Figure 1.4), which illustrates the importance of assessing performance against intended (target) levels and directing actions to improve performance. The next step is to identify appropriate objectives of irrigation and weed management, and specific related performance indicators to which target values can be set. These objectives, performance indicators and targets would constitute the level of service.

The overall aim of irrigation will depend on the specific organisation or project being considered, and the analytical perspective. Chambers (1988) suggests "optimising human well-being" to encompass the many different possibilities. For our purposes it is helpful to expand this into the following aim:

Optimising human well-being by maximisation of agricultural benefits through the controlled delivery and removal of water, while safeguarding the environment, and by making efficient use of water and other resources.

Using the guidelines

Aquatic weeds can create a significant problem for irrigation system managers and individual landowners alike. This problem is one of the factors which prevents irrigation and drainage systems achieving their optimal production. The solution to the problem relies on the determination of the most appropriate maintenance strategy planned over a number of years. This strategy needs to combine recognition and an understanding of the aquatic weeds (i.e. identification of the problem species and the stage of succession which the vegetation has reached (see Section 3.6.2)), suitable control strategies, the engineering demands of a given channel (i.e. the level of service requirement) and the economic implications. The inter-relationship of these different components is summarised in the flow diagram in Figure 1.5 (see page 9).

The process of working through this flow diagram (Figure 1.5) will not only enable an irrigation system manager or landowner to choose an appropriate and cost-effective solution but it will also encourage a greater understanding of the system. For example, careful consideration must be given to deployment of labourers and machinery, and aquatic weed management can be better integrated with desiltation maintenance.

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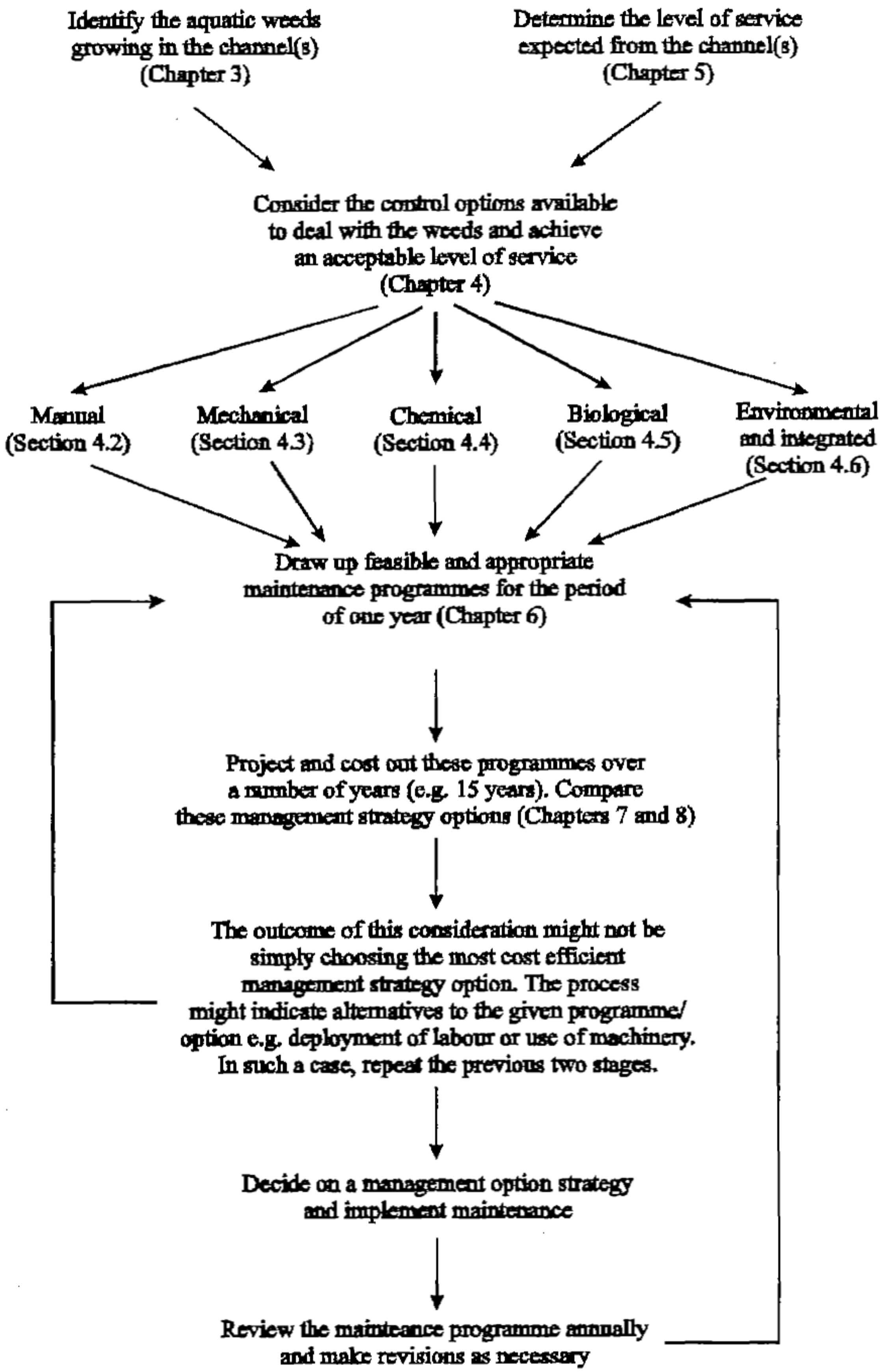

Figure 1.5. Process for determining aquatic weed maintenance strategy

Plate 1.1 Examples of irrigation and drainage channels experiencing differing degrees and types of aquatic weed problems: (a) and (b) Chisumbanje Estate, Zimbabwe; (c) Mwea Irrigation Settlement Scheme, Kenya, and (d) Hadejia Jama'are River Basin Irrigation Scheme, Nigeria.

Plate 1.2 Example of intermediate reservoir, Triangle Estates, Zimbabwe.

CHAPTER 2

IRRIGATION IN SUB-SAHARAN AFRICA

AND CASE STUDIES

2.1 Introduction

Irrigation has a very important role to play in helping agriculture to meet the needs of food production (Table 2.1). This chapter considers the current scale of irrigation schemes and their potential role in the future given rising human population and changes in climate. This review identifies that serious attention should be given to existing irrigation systems to improve efficiency in order to realise their potential. A significant part of such improvements is the management of weeds occurring in the channels and a number of case studies in Zimbabwe and Kenya are presented (Table 2.2) in order to explore channel maintenance and management practices with respect to the growth of weeds.

2.2 Irrigation in sub-Saharan Africa

2.2.1 Types and extent of systems

Sub-Saharan Africa was the focus of the research on which this book is based. Available estimates of the extent and potential of irrigation in sub-Saharan Africa (excluding South Africa) are based on those data obtained in the early 1980's by FAO (1986) (Table 2.1). These must now be regarded as out of date, but they show that about 5 million hectares of land is irrigated in the region, more or less equally split between modern and small-scale or traditional systems. More than 90% of this area is surface irrigation, served by canal systems, as in the developing world as a whole (Field 1990).

Table 2.1 shows the relative lack of irrigation development in sub-Saharan Africa. This becomes even clearer when it is realised how much of the total irrigated area lies in two countries namely Sudan and Madagascar (35% and 20% respectively). However, there is some controversy over the irrigation potential. Estimates vary from 33 million (Table 2.1) to 20 million hectares (Field 1990). The latter would appear to be more realistic in terms of land area where irrigation may be an environmentally and socially acceptable land use, as well as technically feasible and agriculturally useful.

There is considerable scope for more irrigation development. However, it is also commonly reported that much of the existing irrigated area is not performing at maximum efficiency. It has been estimated that as much as 50% of irrigation in sub-Saharan Africa is in need of rehabilitation or modernisation (Field 1990). The failure of systems to achieve their design capacity is due in no small measure to excessive growth of aquatic weeds (Moris and Thom 1990).

Table 2.1. Estimates of irrigated areas in sub-Saharan Africa in relation to irrigation potential, 1982 (FAO 1986). (These figures exclude South Africa. na = not available.)

		Area developed 1982 ('000 ha)			
Country	**Irrigation potential ('000 ha)**	**Modern**	**Small-scale or Traditional**	**Total**	**Developed as % of potential**
Angola	6,700	0	10	10	< 1
Benin	86	7	15	22	26
Botswana	100	0	12	12	12
Burkina Faso	350	9	20	29	8
Burundi	52	2	50	52	100
Cameroon	240	11	9	20	8
CAR	1,900	0	4	4	< 1
Chad	1,200	10	40	50	4
Congo	340	3	5	8	2
Equatorial Guinea	na	na	na	na	na
Ethiopia	670	82	5	87	13
Gabon	440	0	1	1	<1
Gambia	72	6	20	26	36
Ghana	120	5	5	10	8
Guinea	150	15	30	45	30
Guinea Bissau	70	na	na	na	na
Ivory Coast	130	42	10	52	40
Kenya	350	21	28	49	14
Lesotho	8	0	1	1	13
Liberia	na	3	16	19	na
Madagascar	1,200	160	800	960	80
Malawi	290	16	4	20	7
Mali	340	100	60	160	47
Mauritania	39	3	20	23	59
Mauritius	na	9	5	14	na
Mozambique	2,400	66	4	70	3
Niger	100	10	20	30	30
Nigeria	2,000	50	800	850	43
Rwanda	44	0	15	15	34
Senegal	180	30	70	100	56
Sierra Leone	100	5	50	55	55
Somalia	87	40	40	80	92
Sudan	3,300	1,700	50	1,750	53
Swaziland	7	55	5	60	>100
Tanzania	2,300	25	115	140	6
Togo	86	3	10	13	15
Uganda	410	9	3	12	3
Zaire	4,000	4	20	24	1
Zambia	3,500	10	6	16	<1
Zimbabwe	280	127	3	130	46
Total	**33,641**	**2,638**	**2,381**	**5,019**	**14.9**

With the increase in human population, water resources are becoming scarcer per head of population, and "when annual internal renewable water resources are less than 1000 m^3 per head, water availability is considered a severe constraint on socio-economic development and environmental protection" (FAO 1993). This is predicted to occur by the year 2000 in several north African and west Asian countries, and in sub-Saharan Africa in Kenya, Burundi, Rwanda, Botswana, Malawi, Sudan and Somalia.

The irrigated areas in sub-Saharan Africa are small in terms of irrigation per capita. Approximately 10% of the world's population lives in the region but only 2.5% of world irrigation takes place there. The area under irrigation represents some 6% of the total cultivated area but 20% in terms of total production value, with a productivity per hectare of about 3.5 times that of rain-fed agriculture (FAO 1987). With much of the region's irrigation potential not being realised, the potential for this enhanced productivity is also missed.

Africa is struggling to achieve food security, but agricultural production per head has fallen during the last decade. In sub-Saharan Africa as a whole per capita food production decreased by 6% between 1979-81 and 1988-90 (World Development Report 1992). The region has not been able to benefit greatly from the Green Revolution since wheat and rice are not the main staple food crops (Tanton and Stoner 1992).

In a comprehensive overview of irrigation in Africa, Moris and Thom (1990) present the arguments both for and against increasing irrigation in Africa. The case for increasing irrigation rests on a number of interrelated arguments. Where rain-fed agriculture can no longer support the population irrigation may be one of the few options for increasing food production and employment. Irrigation can also be useful for production of valuable export crops to supplement rain-fed agriculture. It can relieve the agricultural limitations imposed by long dry seasons and be used to improve livestock production. Moris and Thom (1990) also suggest conditions in which developing irrigation would not be appropriate policy.

IPTRID (1993) suggest that "compared with the total area of arable land in sub-Saharan Africa, the potential for irrigation development is modest and is often overestimated. In some countries however, it is the only way left to grow enough food for their populations, the size of which has surpassed (or will surpass) the limits of the carrying capacity for traditional rain-fed agriculture".

Moris and Thom's overview also identifies priority areas in irrigation research warranting further attention. They identified key gaps, the lack of which contributed to the low efficiency of African irrigation. One of their findings was that the control of both terrestrial and aquatic weeds is a major problem in African irrigation. Aquatic weeds are seen as a threat to the whole water management system and pose a serious threat to irrigation production. Irrigation canal systems in the tropics provide ideal conditions for aquatic weed growth. Moris and Thom (1990) conclude that more attention should be directed to the problem of weed control, particularly in smallholder production. Another weak link they identify is that of maintenance. They suggest that there is unanimous agreement that poor maintenance constitutes the single most important unresolved problem in African irrigation. There are undoubtedly many factors which contribute to the poor maintenance record. Amongst them will be the lack of effective aquatic weed control in canals and drains.

2.2.2 Future prospects and effects of climatic change

There will be a continuing need to increase food production to keep pace with population growth and urbanisation. Irrigated agriculture has the potential to make an important contribution to this, provided improvements can be made in irrigation performance. The effects of expected climate change on the region are as yet uncertain but a precautionary approach is advisable and the best use of scarce water resources will undoubtedly be essential.

Probably the most important consequence of climate change for agriculture in the tropics is the reduced soil-water availability arising from higher potential evapotranspiration, due to the higher air and land temperatures. Even in the tropics where temperature increases are expected to be smaller than elsewhere and where precipitation might increase, the increased rate of loss of moisture from plants and soil would be considerable (Parry and Swaminathan 1992). The effect on cropping of reduced soil water would, however, vary considerably according to whether it occurs during the growing or non-growing season (Suliman 1990).

Predicted yield reductions in the mid-latitude grain exporting regions would also be likely to result in increased food prices and could seriously influence the ability of food-deficit countries to pay for food imports. Increased prices could improve the economic viability of irrigation projects which has been reduced in recent years by declining food prices.

Suliman (1990) urges that one of the questions that must be tackled scientifically and resolved politically is how agriculture is to adjust in order to not only maintain output but increase it to accommodate population growth. He suggests three types of land use change which may be considered: changes in farmed area, crop type, and crop location. He suggests that irrigation would have an enhanced role to play in the adjustment of future agriculture.

Some points made by Mintzer (1992) can usefully summarise the likely impacts of climate change on sub-Saharan Africa. Like hunger, the stresses that arise from rapid climate changes will fall most heavily on the poorest, the most vulnerable, and those least able to adopt new technology. Global climate change will increase the stress on agricultural systems, potentially decreasing yields at the very time when demand for food is growing dramatically.

The most important impacts may be due to the least predictable aspects of the climate system - changes in the frequency, distribution and severity of extreme weather events. On a global scale substantial increases in the need for irrigation are likely in order to overcome the moisture losses resulting from global warming. Tighter water-management practices will be necessary to yield higher irrigation efficiency (Parry and Swaminathan 1992). The costs of irrigation may rise substantially as a result of water supply limitations.

The pressure to enhance the productivity of irrigation systems has implications for improvements in system management and irrigation related technology (IPTRID 1993). The objectives of this book are to provide information enabling irrigation operators to manage aquatic weeds in irrigation systems more effectively, and hence play a part in the drive for improved efficiency and production.

2.3 Case study schemes

Fieldwork for this book was undertaken in Zimbabwe and Kenya on several different schemes which covered various sizes and management types. These are listed in Table 2.2. Most data were collected from Chisumbanje Estate in Zimbabawe, and the Mwea Irrigation Settlement Scheme in Kenya. The other schemes, the Triangle Sugar Estates, Zimbabwe, and the Gem Rae Irrigation Project, Kenya, are described in detail below to illustrate the context for weed management. A different view was obtained by an additional study of a drainage system at Welland and Deepings Internal

Drainage Board in UK, and this is also described below. Further fieldwork was undertaken in northern Nigeria.

Table 2.2. Summary of main characteristics of irrigation schemes studied

Country	Scheme	Size (ha)	Management	Soil type	Primary crop(s)	Rainfall (mm yr^{-1})
Zimbabawe	Chisumbanje Estate	2,400	Agricultural and Rural Development Authority (ARDA)	Vertisols	Cotton and wheat	630
Zimbabawe	Triangle Estate	13,863	Tongaat-Hulett (private company)	Sandy loam, loamy sand and sandy clay loam	Sugar cane	550
Kenya	Mwea Irrigation Settlement Scheme	12,140	National Irrigation Board (NIB)	Vertisols	Rice	
Kenya	Gem Rae	118	Scheme Committee	Medium to heavy, dark grey or black clays	Rice	1,250

2.3.1 Chisumbanje Estate, Zimbabwe

2.3.1.1 Physical environment

Chisumbanje Estate (Figure 2.1) is one of 26 agricultural estates operated by the parastatal organisation the Agricultural and Rural Development Authority (ARDA). The estate is located in the Ndowoyo Communal Area, in the south-east lowveld of Zimbabwe on the east bank of the Sabi (Save) River approximately 100 km downstream of Birchenough Bridge and about 80 km north of Chiredzi. The primary crops are cotton and wheat.

Figure 2.1. Layout of Chisumbanje Estate irrigation scheme

Zimbabwe is divided into five Natural Regions (I to V) on the basis of the adequacy and reliability of rainfall. The Chisumbanje area is classified into Natural Region V which has too low and erratic a rainfall for reliable crop production. The climate is semi-arid with an average annual rainfall of 630 mm, over 80% of which is received between November and March and is generally associated with high intensity thunderstorms which can cause damage to crops.

The average annual temperature is 22°C, with monthly averages ranging from 15°C in July to 25.5°C in January. Mean maximum temperatures of over 32°C occur during the summer months (October to March) and absolute maximum temperatures of up to 43°C have been recorded. The coldest months are June and July when mean minimum temperatures are below 9°C. Frosts, however, are rare due to the low elevation (approximately 400 m asl). High temperatures and low humidities contribute to an annual precipitation deficit of the order of 1400 mm and irrigation is necessary throughout the year for successful crop production.

The soils are dominated by vertisols derived from basalt and described as natural flood irrigation soils with an automatic water acceptance rate. These are fertile, black clay soils with characteristic soil mulching and high water retention properties. They experience marked expansion and contraction with changes in moisture content. When dry, the soils shrink and crack and the soil surface becomes very friable. The cracks, which extend into the sub-soils, gradually fill with loose surface granules. This creates great pressure in the sub-soils, resulting in heaving and churning when water is re-admitted to the soil profile and the soils swell. Such movement negates the requirement for ploughing or deep cultivation and is the basis for the expression 'self-tilling soils.'

2.3.1.2 Irrigation and drainage systems

Development of Chisumbanje Estate commenced in 1966 when 625 ha of flood irrigated land were established. The irrigated area was expanded by a further 500 ha in 1968, and in 1973 an additional 1,200 ha was commanded. Presently, an irrigated area of approximately 2,400 ha is operated by ARDA, including some 400 ha allocated to 117 smallholder settlers with holdings of 3-6 ha (Figure 2.1).

Irrigation is provided by pumping water from the normal flow of the Sabi River. The existing pumping station was constructed in 1978 and has a capacity of 1.84 m^3 /s. During the dry, winter months, river flow is occasionally supplemented by releases from the Ruti and Rusape Dams, respectively located 175 km and 275 km upstream. A new pumping station, linked to a set of infiltration boreholes in the river bed is currently under construction. This will allow the procurement of large volumes of water from the river-bed when surface flows fail during the dry season.

Water is conveyed by pipeline from the pumping station to the estate. The pipeline discharges into a concrete-lined supply canal which, in turn, gives rise to a concrete-lined secondary canal on the western side of the estate, and an unlined branch canal on the eastern side. These canals deliver water to three intermediate or storage reservoirs (known locally as dams) with capacities of 31,000 m^3, 62,000 m^3 and 160,000 m^3. Water is distributed to the fields by concrete-lined canals of 0.07 m^3/s and earthen canals ranging in capacity from 0.14-0.50 m^3/s. Irrigation is achieved via furrows, using siphons to draw water from the canals.

The drainage system comprises a network of open drains which ultimately discharge into the main drainage line formed by the Jerawachera and its tributary streams.

ARDA is wholly responsible for the operation and maintenance of the entire irrigation and drainage system.

The estate is headed by an Estate Manager who is responsible for the operational and administrative affairs of the estate. He is assisted by seven departmental heads - the Field Manager, Workshop Manager, Building and Maintenance Manager, Administration Officer, Estate Accountant, Settlement Officer and Security Officer.

Estate management activities involve the farming of summer cotton and winter wheat on irrigated land. Although irrigated cotton and wheat offer a technically sound rotation combination, they present a timing problem. Wheat must be sown early in May if it is to receive sufficient cold induction for flowering and tillering, and it requires approximately 130 days in the field. On the other hand, cotton should be planted in November and picking should commence in May.

Present practice is to plant cotton between 15 October and 15 November, the slightly earlier period of planting being dictated by the requirements of the subsequent wheat crop. Irrigation is normally necessary every 20-30 days, depending on the stage of growth, evapotranspiration rates and effective rainfall. Cotton is harvested by hand; picking commences at the beginning of March when the first bolls are open and is completed by the end of May. The rate of picking is determined by the timing of wheat sowing which should occur between 25 April and 15 May, although in practice sowing may extend from mid-April into June.

2.3.1.3 Aquatic weed management

A range of different aquatic weeds occur in the irrigation and drainage channels (see Tables 3.1 and 3.2) and the management of the aquatic weeds on Chisumbanje Estate centres on manual methods of control, principally hand-pulling and the use of 'slashers', sickles and hoes. Slashers are long, sword-like blades, the cutting end (10-15 cm) of which is bent at a right-angle to the shaft (Plate 2.1). The blade is swung, to and fro, to slash the vegetation just above ground level. The fragments of vegetation produced are not usually removed from the channels and may propagate themselves downstream.

Slashers are only effective for cutting vegetation in dry channels. Submerged plants are cut using sickles and the pared material is often removed from the channel and dumped on the channel bank.

Shallow hoeing along the banks and beds of channels removes all the above-ground plant material and some of the root systems. The method is generally more effective for clearing channels of vegetation using a sickle, but has an associated problem of drawing earth from the banks into the centre of the channel, thereby altering the channel profile.

In some instances, mechanical methods of weed control are employed. Roming disks (circular blades, drawn in rows behind tractors), are used to cut unwanted vegetation occurring in field drains. Such action is determined by local labour availability and there can be shortages at the time of the control operation.

During fallow seasons in dry canals with large quantities of accumulated sediment, a tractor and plough might be used to turn the sediment which is then shovelled out by hand. Although the exercise is aimed at improving the hydraulic performance of canals, it has obvious benefits for weed control. The recovery of vegetation in canals after ploughing, although not quantified, is reported to be slower than after other weed control operations. However, the technique is considered too expensive to be incorporated into a cycle of regular maintenance.

Most operations to control weeds in irrigation and drainage channels on Chisumbanje Estate are carried out, on a task basis, by seasonal labourers. Only during slack periods in the agricultural calendar do permanent workers participate. Labourers are loaned tools by the estate but are not provided any protective clothing. It is common to see men, wearing nothing but shorts, working in channels containing water. This exposes the labourers to the risk of contracting schistosomiasis.

The timing of weed control operations is often governed by agricultural activities and the demand for labour in the fields. Thus, slack periods, such as 'between crops' (i.e. after cotton-picking before wheat is sown, and after wheat harvesting before cotton is planted) are often associated with weed control.

Weed management on Chisumbanje Estate is summarised in Table 2.3.

2.3.2 Triangle Group Sugar Estates, Zimbabwe

2.3.2.1 Physical environment

The Triangle Group Sugar Estates are large-scale, commercial sugar estates owned by the South African-based company Tongaat-Hulett. The estates (hence referred to as Triangle Estates) are located in the south-east lowveld of Zimbabwe, in the District of Chiredzi (Natural Region V). Most of the cultivated area lies at an altitude of 410 m asl, on the east bank of the Mutirikwe River, upstream of the confluence with the Runde River.

The climate in the Triangle area is semi-arid. The average annual rainfall received is around 550 mm but rainfall is extremely variable. More than 80% of the rain falls between November and March, but 'guti' conditions are experienced at other times of the year. Mean daily temperatures for the year vary from 26°C in January to 16°C in July (averaging 22°C for the year). January is usually the hottest month in the year (mean daily maximum of 32°C) whilst the coolest month is normally July (mean daily minimum of 7°C). Frosts rarely occur.

Three main soil types dominate the Triangle area - sandy loam (clay content 18%), light-textured and free-draining; loamy sand (clay content 5 - 20%) the poorest soils on Triangle Estates, and sandy clay loam (clay content 30%) potentially the most productive soils on Triangle Estates. Generally, the soils on Triangle Estates are rich enough for sugar cane production, but leaching can be a problem on lighter soils and drainage can be limited on the heavier soils along natural drainage lines.

2.3.2.2 Irrigation and drainage systems

Irrigation on Triangle Estates has a long history, dating back to the 1930's. Presently, the irrigable area amounts to 13,863 ha of which 5,900 ha is overhead irrigation and 7,963 ha is furrow irrigation. Water for irrigation is derived from several sources. The greatest volume of water (183,512 Ml) is supplied from Mutirikwe Dam (Lake Kyle) from which water flows 100 km down the Mutirikwe River via Bangala Dam to the Nyajena (Esquilingwe) Weir. Here it passes into the Kyle Canal which has a peak flow of 20 cumec and transports the water a further 56 km to Triangle Estates.

Water is stored on Triangle Estates in 105 intermediate reservoirs locally known as dams. It is distributed to the fields via some 400 km of canals approximately 250 km of which are concrete-lined.

Table 2.3. Summary of aquatic weed management in irrigation and drainage systems on Chisumbanje Estate, Zimbabwe. (A Section is a division of the Chisumbanje Estate, hence Section A2 and Section B2)

Irrigation Unit	Dimensions	Principal Plants	Control Operation	Task (m^2/day)	Unit Cost of Control Operation (Z$/$m^2$) *a*	Effectiveness of Control Operation
Concrete-lined main supply canal	*c*. 4.50 m wide 1.84 m^3/s	Grasses alongside canal	Slashing alongside canal - three times a year, during wet season	-	-	-
Earthen branch canal	*c*. 1.50 m deep *c*. 12.50 m wide	*Commelina* sp. *Cyperus articulatus* *Eriochloa* sp. *Ludwigia stolonifera* *Persicaria* sp.	Slashing within channel - three times during wet season and twice during dry season	-	-	Effective for up to 4 weeks Effective for 6-8 weeks
			Hoeing within channel - twice a year, before crop establishment in May and October	-	-	
Concrete-lined secondary canals	-	Grasses alongside canal	Slashing alongside canal - up to three times a year during wet season	-	-	-

Table 2.3. Summary of aquatic weed management in irrigation and drainage systems on Chisumbanje Estate, Zimbabwe (cont.)

Irrigation Unit	Dimensions	Principal Plants	Control Operation	Task (m^2/day)	Unit Cost of Control Operation (Z$/$m^2$) a	Effectiveness of Control Operation
Night-storage dams	31,000 m^3 - 160,000 m^3 capacity	*Cyperus articulatus* *Commelina diffusa* *Dichanthium annulatum* *Ischaemum afrum* *Paspalum scrobiculatum* *Persicaria* sp.	No maintenance required	-	-	-
Concrete-lined field canals	0.07 m^3/s	*Potamogeton* sp. Grasses and broad-leaved plants alongside canal	Slashing or hoeing alongside canal - up to three times a year, twice during wet season and once during dry season before wheat establishment	-	-	Slashing effective for up to 4 weeks; hoeing effective for 6-8 weeks
Earthen field canals						
Section A2 canals	c.0.60-0.80m deep c.3.50-4.00m wide 0.140m^3/s	*Dichanthium annulatum* *Echinochloa colona* *Ludwigia stolonifera*	Hoeing within channel - twice a year, before crop establishment in May and October	300 (75 m of canal)	0.026 - 0.050	-

Table 2.3. Summary of aquatic weed management in irrigation and drainage systems on Chisumbanje Estate, Zimbabwe (cont.)

Irrigation Unit	Dimensions	Principal Plants	Control Operation	Task (m^2/day)	Unit Cost of Control Operation (Z$/$m^2$) a	Effectiveness of Control Operation
			Slashing within channel as required before irrigations	600 (150 m of canal)	0.013 - 0.025	-
			Ploughing within channel	-	-	-
Settlers blocks canals	*c.* 0.55-0.90 m deep *c.* 3.50-4.80 m wide 0.280 m^3/s	*Commelina* sp. *Echinochloa colona* *Lucwigia stolonifera*	Slashing alongside canal	-	-	-
			Hoeing/hand-pulling within channel	-	-	-
			Ploughing within channel	-	-	-
Section B1 canals	c.0.50-0.95 m wide c.4.40-5.80 m wide 0.200-0.600 m^3/s	*Commelina* sp. *Cyperus difformis* *Ludwigia stolonifera* *Potamogeton* sp.	Hoeing within channel as required before irrigations	750 (150 m of canal)	0.011-0.020	Effective for 6-8 weeks, longer in dry season
			Slashing within channel as required before irrigations	1250 (250 m of canal)	0.006-0.012	Effective for up to 4 weeks
			Ploughing within channel			

Table 2.3. Summary of weed management in irrigation and drainage systems on Chisumbanje Estate, Zimbabwe (cont.)

Irrigation Unit	Dimensions	Principal Plants	Control Operation	Task (m^2/day)	Unit Cost of Control Operation (Z$/$m^2$) a	Effectiveness of Control Operation
Section B2 canals	*c.* 0.50 - 0.90 m deep *c.* 4.70 - 5.70 m wide 0.367 m^3/s	*Cyperus difformis* *Ludwigia stolonifera* *Potamogeton* sp.	Hoeing within channel - twice a year before crop establishment in May and October	250 (100 m of half-canal)	0.032 - 0.060	-
			Slashing within channel as required before irrigations	500 (200m of half-canal)	0.016 - 0.030	-
			Ploughing within channel	-	-	-
Field drains		*Cyperus articulatus* *Dichanthium annulatum* *Eriochloa* sp. *Sesbania* sp. *Typha latifolia*	Slashing and burning within drain - once a year, before cotton establishment	-	-	-
			Roming within drain - once a year, between January and March	-	-	-
Secondary drains		Corchorus olitorius Eriochloa sp. Phragmites australis Typha latifolia	Slashing and burning within drain - once a year	-	-	-

Table 2.3. Summary of weed management in irrigation and drainage systems on Chisumbanje Estate, Zimbabwe (cont.)

Irrigation Unit	Dimensions	Principal Plants	Control Operation	Task (m^2/day)	Unit Cost of Control Operation (Z$/$m^2$) a	Effectiveness of Control Operation
Main drain		*Cyperus involucratus* *Dichanthium annulatum* *Echinochloa colona* *Eriochloa* sp. *Typha latifolia*	Hand-pulling in excavated section - intervals of six weeks	-	-	-
			Slashing and burning within drain before crop establishment in May and October and as required before irrigations	-	-	-

a Figures based on rates for seasonal and permanent labour respectively

Drainage of Triangle Estates centres around the Cheche, Kamba and Makari Rivers and their tributary streams. In-field drains unite to form main drains which then discharge, via estate drains, into the above river systems. These rivers ultimately discharge into the Mutirikwe River.

The command area of Triangle Estates is divided into areas and sections. For example, Section 19 extends for 675.5 ha, irrigation water entering the section via a concrete-lined main canal. From the main canal, water can either be diverted to night-storage dams, or distributed directly to the fields by concrete-lined crest canals (or feeders) which give rise to concrete-lined feeders and earth feeders. Surface water is removed from the fields by shallow surface drains which discharge into deep in-field drains or main drains. These also receive water from tile-drains. Drainage leaves the estate via main watercourses known as estate drains.

2.3.2.3 Organisation and management

All agricultural operations are directed by the Agriculture Division of Triangle Estates, headed by the Director of Agriculture, and sub-divided into four departments - the Agriculture Department, the Agriculture-Technical Department, the Agronomy and Training Department and the Cane Haulage Department.

The Agriculture Department, under the supervision of the Agriculture Manager, undertakes all field operations on Triangle Estates, including land preparation, planting, irrigation at the section-level and harvesting. Triangle Estates are divided into five areas, each headed by a Field Manager. The areas are, in turn, split into sections (totalling 30 and ranging in size from 320 ha to 659 ha) administered by Section Managers. Each section is run as a separate farm entity under a bonus system.

The Agriculture-Technical Department is responsible for agricultural and irrigation engineering on Triangle Estates. It is involved in the design and construction of irrigation and drainage works, and the operation and maintenance of the irrigation network, including the 35 pumping stations, as far as the section-level. Whilst the department monitors the distribution and use of irrigation water across Triangle Estates it is not responsible for irrigation at the field level, which comes under the Agriculture Department.

2.3.2.4 Aquatic weed management

A range of aquatic species grow in the irrigation and drainage channels and night-storage dams (Table 2.4). The use of stillage effluent as a fertiliser generated during ethanol production from the sugar cane has reduced dependence on manufactured fertilisers. However, it is also believed to be responsible for an increase in both the number and quantity of weed species occurring in the drainage lines.

Table 2.4. Summary of weed management in irrigation and drainage systems on Triangle Estates, Zimbabwe

Irrigation Unit	Dimensions	Principal Plants	Control Operation	Task (m^2/day)	Unit Cost of Control Operation (Z$/$m^2$)	Effectiveness of Control Operation
Main canal (concrete-lined)	*c.* 0.50 - 1.00 m deep *c.* 1.50 - 2.00 m wide	*Cynodon dactylon* *Echinochloa* sp. *Euphorbia hirta* *Euphorbia serpens* *Gomphrena celesoides* *Portulaca oleracea* *Stenotaphrum secundatum*	Slashing along shoulders of canal - three times a year	100	0.10	Effective for up to 4 weeks in wet season; and longer in dry season
Night-storage dams	3.0 Ml to 19.5 Ml capacity	*Cyperus articulatus* *Panicum repens* *Persicaria* sp. *Typha latifolia*	Slashing inside dam - three times a year	150		-
			De-silting (mechanically)	-		Effective for up to 5 years
Crest feeders (concrete-lined)	*c.* 0.30 - 0.70 m deep *c.* 0.50 - 1.00 m wide	See Main canal	Hoeing along shoulders of canal - four times per year	150	0.07	Effective for up to 4 weeks in wet season and 3-4 months in dry season
Concrete feeders	*c.* 0.30 m deep *c.* 0.50 m wide	See Main canal	Slashing along shoulders of canal - four times per year	100	0.10	Effective for up to 4 weeks in wet season and longer in dry season

Table 2.4. Summary of weed management in irrigation and drainage systems on Triangle Estates, Zimbabwe (cont.).

Irrigation Unit	Dimensions	Principal Plants	Control Operation	Task (m^2/day)	Unit Cost of Control Operation (Z$/$m^2$)	Effectiveness of Control Operation
Earth feeders	*c.* 0.30 - 0.50 m deep *c.* 0.50 - 1.25 m wide	*Cynodon dactylon* *Euphorbia hirta* *Launaea cornuta* *Stenotaphrum secundatum*	Hoeing within channel and along shoulders of canal - four times a year	150	0.07	Effective for up to 4 weeks in wet season and 3-4 months in dry season
Surface drains	c. 0.30 m deep c. 0.50 m wide	*Cyperus esculentus* *Echinochloa* sp. *Eclipta alba* *Gomphrena celesoides* *Nesaea* sp. *Oldenlandia* sp.	Hoeing within drain - twice a year	150	0.07	-
In-field drains	*c.* 1.00 - 2.00 m deep > 1.50 m wide	*Cynodon dactylon* *Cyperus difformis* *Cyperus involucratus* *Echinochloa* sp. *Eclipta alba* *Euphorbia hirta* *Eragrostis* sp. *Ludwigia stolonifera* *Nesaea* sp. *Stenotaphrum secundatum* *Typha latifolia*	Slashing within drain- four times a year	100	0.10	Effective for up to 4 weeks in wet season and 3-4 months in dry season
			Hoeing / re-aligning drain profile - once a year, in June	5 m^3/day	1.954/m^3	-

Table 2.4. Summary of weed management in irrigation and drainage systems on Triangle Estates, Zimbabwe (cont.)

Irrigation Unit	Dimensions	Principal Plants	Control Operation	Task (m^2/day)	Unit Cost of Control Operation (Z$/$m^2$)	Effectiveness of Control Operation
Main drains	> 1.50 m deep > 2.00 m wide	See In-field drains	Slashing within drain - twice a year	150	0.10	-
			Hoeing / re-aligning drain profile - once a year, in June	5 m^3/day	1.954/m^3	-
			Mechanical clearance once every two years	120 m/day	15.00	*Typha latifolia* recovers within 12 months
Estate drains	Variable	*Cyperus involucratus* *Ludwigia stolonifera* *Phragmites australis* *Typha latifolia*	Slashing within drain- once a year	150	0.07	-
			Mechanical clearance once every two years	120 m /day	15.00	*Typha latifolia* recovers within 12 months

Table 2.5. Weed management in irrigation and drainage channels at Mwea Irrigation Settlement Scheme

Channel	Dimensions	Flow Regime	Principal Weeds	Maintenance Activity
Main Canal[a]	13330 m total length 2.90-6.50 m base width 0.80-1.50 m canal height 0.56-1.31 m water depth 1.95-6.35 $m^3 s^{-1}$	Flow year round - water supplied for domestic use as well as irrigation	*Acmella caulorhiza* *Commelina* sp. *Cyperus dives* *Polygonum senegalense*	Dredging to remove silt and weeds, once per year, in January/February Manual clearance of weeds, using pangas, hoes or spades, twice per year in June and September
Branch Canal[a]	45580 m total length 0.30-3.50 m base width 0.30-1.40 m canal height 0.12-1.23 m water depth 0.04-2.73 $m^3 s^{-1}$	Flow dependent on cropping program - February to November	*Acmella caulorhiza* *Ageratum conyzoides* *Commelina* sp. *Cyperus latifolia* *Eclipta alba* *Leersia hexandra* *Ludwigia abyssinica* *Panicum repens* *Polygonum senegalense* *Rhynchosia* sp.	Dredging to remove silt and weeds, once per year, before area served by canal is irrigated Manual clearance of weeds, using pangas, hoes or spades, twice per year
Main / Unit Feeder	*c.* 1.50-3.00 m bank top 0.028 $m^3 s^{-1}$ / 20.25 ha (1 cusec / 50 acres)[b]	Flow dependent on cropping program - February to November	*Acmella caulorhiza* *Ageratum conyzoides* *Centella asiatica* *Commelina* sp. *Cynodon dactylon* *Leersia hexandra*	Dredging to remove silt and weeds, infrequently, as required Manual clearance of weeds, using pangas, hoes or spades, twice per year, during production period
Feeder	*c.* 0.50-2.00 m bank top 0.028 $m^3 s^{-1}$ / 20.25 ha (1 cusec / 50 acres)[b]	Flow dependent on cropping program - February to November; period varies from 6-10 months	*Commelina* sp. *Cynodon dactylon* *Leersia hexandra*	Manual clearance of silt and weeds, using pangas and hoes, three times per year, before flooding, before transplanting and before top-dressing
Field Drain	*c.* 1.50-3.00 m bank top 0.003 $m^3 s^{-1}$ / 1 ha) (0.05 cusec / acre)[b]	Flow dependent on cropping program - February to December; period varies from 6-10 months	*Commelina* sp. *Cynodon dactylon* *Echinochloa colona* *Fimbristylis* sp. *Leersia hexandra* *Ludwigia stolonifera*	Dredging to remove silt and weeds, infrequently, as required Manual clearance of weeds, using pangas and hoes, three times per year, before flooding, before transplanting and before draining for harvest
Collector Drain	*c.* 1.50-3.50 m bank top 0.003 $m^3 s^{-1}$ / 1 ha) (0.05 cusec / acre)[b]	Flow dependent on cropping program - February to December	*Commelina* sp. *Cynodon dactylon* *Leersia hexandra* *Ludwigia stolonifera* *Panicum repens*	Dredging to remove silt and weeds, infrequently, as required Manual clearance of weeds, using pangas, hoes or spades, twice per year, in April/May and November/December
Main Drain[a]	32800 m total length 1.50-15.00 m base width 0.70-3.20 m canal height 0.42-2.83 m water depth 1.00-40.90 $m^3 s^{-1}$	Flow dependent on cropping program - February to December	*Commelina* sp. *Cynodon dactylon* *Echinochloa colona* *Echinochloa pyramidalis* *Leersia hexandra* *Marsilea* sp. *Polygonum senegalense* *Typha latifolia*	Dredging to remove silt and weeds, once per year Manual clearance of weeds, using pangas, hoes or spades, two or three times per year, before rains

[a] design specifications JICA (1989)
[b] design specifications Chambers and Moris (1973)

The management of vegetation in irrigation and drainage channels and night-storage dams on Triangle Estates is given considerable accord and general recommendations for weed control operations have been issued by the Agronomy and Training Department. These take into consideration soil conservation measures linked to plant growth in and along channels. The vegetation in irrigation and drainage channels and night-storage dams is generally controlled by manual techniques, based around the use of slashers, pangas, hoes and shovels. To try and lessen the problem of soil erosion on Triangle Estates, it is recommended that the growth of the grasses *Cynodon dactylon* and *Stenotaphrum secundatum* be actively encouraged on the 'shoulders' (earthen berms) along concrete-lined and earth canals and on the banks of drainage channels. *Cynodon dactylon* is also advocated to stabilise the soils inside earth feeders. In this respect, the Agronomy and Training Department suggests the adoption of weed control techniques, in the following order, according to requirements: hand-pulling, slashing, hoeing or shovelling. However, such recommendations are not always adhered to by operational staff and it is common to see channels completely denuded of vegetation.

Each year, for two or three weeks in June, the Regional Water Authority closes the Kyle Canal for maintenance. During this period, Triangle Estates takes the opportunity to close down its irrigation and drainage systems for maintenance. Weed control operations are usually carried out by seasonal labour. However, at this time of year, permanent staff are also drafted to maintenance operations since they are not required to perform their normal duties. The post-harvest stress period (time between cane-cutting and stalk elongation) and drying off period (when water is withheld from the field before cutting) also allow for the deployment of permanent staff to weed control operations. Workers are issued with tools, protective clothing (gumboots and smock), a water container and a daily food supplement of mahewu (a form of gruel). Payment is organised on a task basis at the rate (in 1994) of Z$9.77 per day (Z$254.00 per month) for seasonally employed labour and Z$12.96 (Z$337.00 per month) for permanent labour.

During the wet season when plant growth is reported to be most prolific, the majority of the available labour is employed in the removal of crop weeds, and maintenance of irrigation and drainage channels is of secondary importance. The management of vegetation in the drainage network particularly tends to be reactive, carried out in response to flooding.

The night-storage dams provide for a rich flora including a range of grasses, sedges and broad-leaved plants with abundant growth of the emergent weeds *Typha latifolia*, *Panicum repens*, *Cyperus articulatus*, *Schoenoplectus* sp. and *Persicaria* spp. sometimes extending across the entire bed of shallow dams. An abundance of the submerged weed *Najas* sp. has also been recorded. Ordinarily the vegetation in the dams is controlled, by slashing, approximately three times each year. In some instances, this operation requires that the dam be drained.

Many of the dams are heavily silted and operate considerably below design capacity. As part of a programme to reinstate dams, through the mechanical removal of silt, attention is being directed towards the control of vegetation in these structures. The original design of many night-storage dams is such that their cross-sectional profile is very shallow, a condition which promotes invasion of the water body by emergent plants including those species described above. It is now the policy of the Agriculture-Technical Department to re-profile night-storage dams during the course of de-silting operations to provide steeper slopes and a water depth greater than 1.5 m in order to prevent re-colonisation by emergent vegetation. In some instances, a thick sward of the creeping grass *Stenotaphrum secundatum* has also been encouraged in order to discourage the re-growth of the emergent weed *Typha latifolia*. The regular cycle of draw-down in these dams is also believed to retard the development of emergent vegetation.

Very little vegetation occurs in the concrete-lined canals (including main canals, crest feeders and concrete feeders). Those plants which are present (e.g. *Eclipta alba* and *Echinochloa* sp.) usually arise from cracks in the concrete lining or are rooted above the lining and trail into the channels. The shoulders which run alongside the concrete-lined canals support grasses and broad-leaved plants such as *Cynodon dactylon, Stenotaphrum secundatum, Euphorbia serpens, Euphorbia hirta, Portulaca oleracea,* and *Gomphrena celesoides.* The development of these species is checked by slashing or hoeing, three or four times annually. Such operations usually take place once during the dry season and once every month during the wet season.

The earth feeders generally support a sparse growth of the grasses *Cynodon dactylon* and *Stenotaphrum secundatum* which frequently occur along the shoulders of the earth feeders and occasionally invade the channels; other broad-leaved species which exist in and along the earth feeders include *Euphorbia hirta, Launaea cornuta* and *Boerhavia* sp. Excess growth of these plants is removed by slashing, on average, four times per year.

The surface drains are very narrow, shallow depressions which trap any run-off from the furrows between the cane lines. Plants recorded in the surface drains include the emergent weeds *Cyperus esculentus, Echinochloa* sp., *Eclipta alba, Gomphrena celesoides, Nesaea* sp. and *Oldenlandia* sp. These are generally removed from the drains by hoeing twice annually.

The main and in-field drains tend to be deep, relatively narrow watercourses which flow year-round. During the dry season, they operate at a level far below their capacity, but during the wet season they are required to remove large volumes of water from the cane fields. Many sub-surface tile-drains discharge into the main and in-field drains, and if these are to function correctly, it is imperative that the vegetation occurring in the open drains is controlled to allow 1.5 - 2.0 m freeboard. The flora in the main and in-field drains is fairly diverse, including grasses (e.g. *Cynodon dactylon, Stenotaphrum secundatum* and *Phragmites australis*), sedges (e.g. *Cyperus difformis, Cyperus esculentus* and *Cyperus involucratus*) and broad-leaved species (e.g. *Commelina* sp. and *Ludwigia stolonifera*). However, the emergent weed *Typha latifolia* is considered to be the major weed in the drainage lines.

The maintenance of the drainage lines takes two forms: the removal of vegetation as part of de-silting operations; and the removal of vegetation by slashing. The former operation generally takes place around the June shut-down period on an annual basis, whilst the latter task occurs two to four times, usually on an *ad hoc* basis, in response to flooding during the wet season. Most Section Managers aim to maintain the entire length of their drainage lines during the course of a year.

In years past, more than 100 km of the main drainage lines were cleared mechanically, every two years, using ditch-cleaning buckets mounted on the arms of hydraulic excavators. However, those excavators are now defunct, but there is an intention to replace them.

2.3.3 Mwea Irrigation Settlement Scheme, Kenya

2.3.3.1 Physical environment

Mwea Irrigation Settlement Scheme (hence referred to as Mwea ISS) is located near Embu, in the Kirinyaga District of Central Province, Kenya. It extends over 12,140 ha and draws water for irrigation from the Thiba and Nyamindi Rivers, both tributaries of the Tana River which flows to the west of the scheme (Figure 2.2). Surplus irrigation water and excess precipitation are drained from the scheme into the Thiba and Nyamindi Rivers.

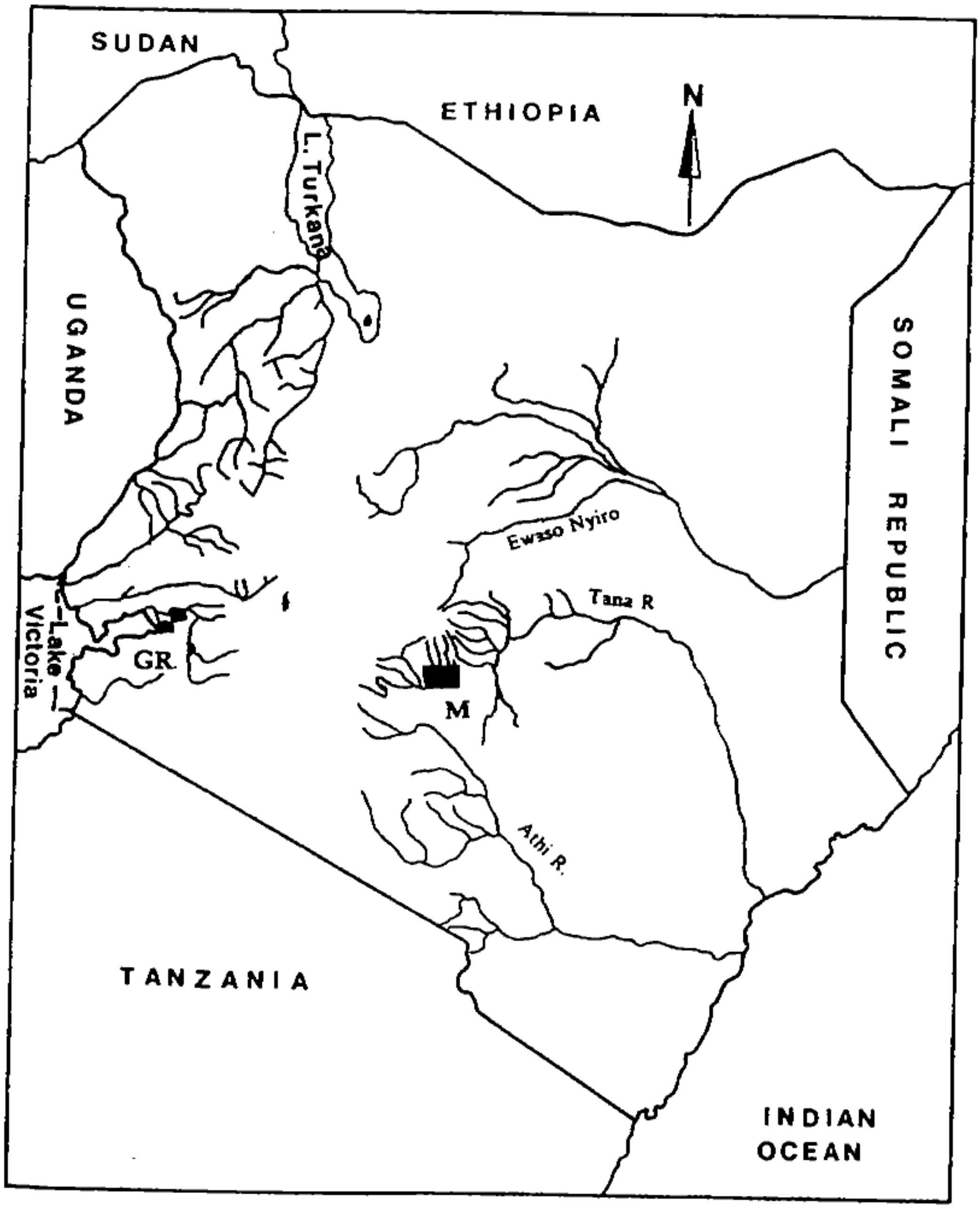

Figure 2.2. Location of the Mwea Irrigation Settlement Scheme (M) and Gem Rae Irrigation Project (GR), Kenya

Mwea ISS is the largest producer of rice in Kenya, accounting for over 70% of the total production (JICA 1988). The scheme is managed by the National Irrigation Board (NIB), and supports approximately 300 NIB administrative staff in eight departments (Figure 2.3). Crop production, however, is carried out by tenant farmers in accordance with a cropping schedule prepared by the NIB management (Figure 2.4). Each farmer is licensed to cultivate 1.6 ha (4 acres) of irrigated rice. Farm inputs such as land preparation services, irrigation water, fertilisers and transport for harvested paddy are supplied for a nominal fee by the NIB. Farmers are required to deliver all their produce to the NIB for marketing.

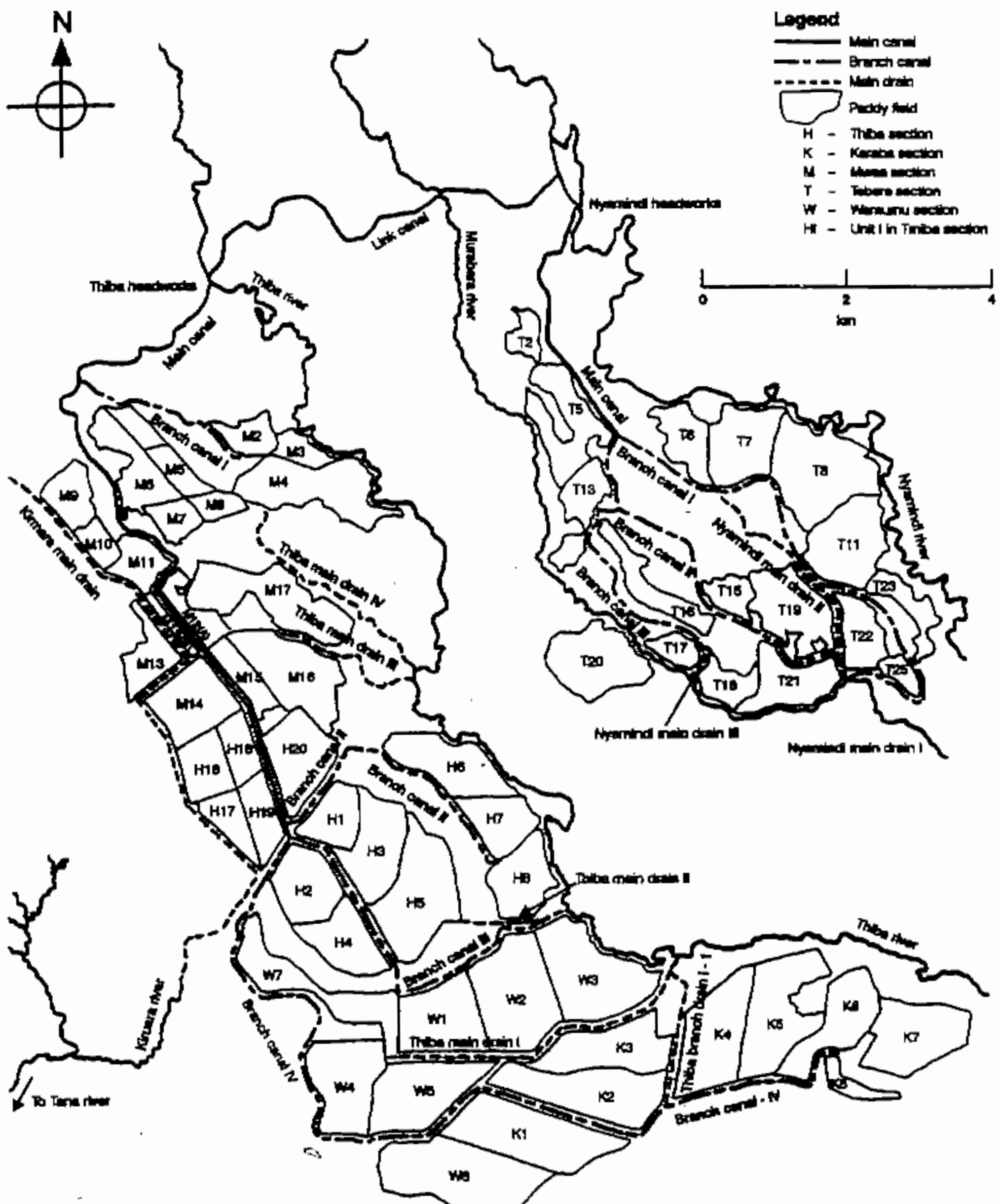

Figure 2.3. Layout of the Mwea Irrigation Settlement Scheme

2.3.3.2 Irrigation and drainage system

Mwea ISS is divided into sections (e.g. Thiba Section in Figure 2.2), each of which is administered by a NIB Irrigation Officer. The individual sections vary in size from 1,900 - 3,000 ha and are sub-divided into units (e.g. Unit H1 of Thiba Section in Figure 2.2) which, in turn, are split into fields. From the headworks on the rivers, water is conveyed by gravity through a network of open channels via link canals and main canals (primary channels) and branch canals (secondary channels) into the sections (Figure 2.2). Main or unit feeders (tertiary channels) carry water from the main and branch canals to the individual units (Figure 2.5). Within the units, water is supplied to individual fields by feeders (quaternary channels) (Figure 2.5). Each feeder serves two lines of fields. The standard field measures 0.4 ha (1 acre) and is rectangular, with one short side abutting on the feeder and the other adjoining the field drain.

Drainage at Mwea ISS is provided by a system of drains which discharge into one of four rivers: the Kiruara, Thiba, Murubara and Nyamindi. Excess water from the fields is collected by field drains (quaternary channels) which run almost parallel to the feeders on the opposite sides of the fields. Field drains discharge into collector drains (tertiary channels) which evacuate water from the units (Figure 2.5). In places where units are located along a river, field drains or collector drains may deliver drainage water directly to the river; elsewhere they flow into main drains (primary or secondary channels). The layout of the irrigation and drainage systems at Mwea ISS is typical of schemes throughout the developing world (see, for example, Kay 1986).

Most of Mwea ISS is underlain by vertisols, i.e. impermeable black cotton soils. Consequently, the irrigation and drainage networks comprise almost entirely of unlined open channels. Only in areas where the primary and secondary canals pass through more permeable red soils are short reaches of the channels concrete-lined.

The main crop grown at Mwea ISS is rice and the cropping cycle is summarised in Figure 2.4.

A range of aquatic weeds species grow in the channels (Table 3.3) reducing the efficiency of the system. The NIB, in conjunction with the tenant farmers, has developed a channel maintenance programme integrated into the crop production cycle (Table 2.5, page 30). The NIB spends ZSh. 11.5 million per year on maintenance at Mwea ISS, i.e. ZSh. 2,000 ha^{-1}.

Schistosomiasis is present in the area and labourers working in the water are at risk of contracting the disease.

2.3.3.3 Aquatic weed management

The management of weeds in irrigation and drainage facilities at Mwea ISS is apportioned between the NIB Works Department and the tenant farmers. The Works Department is wholly responsible for the primary and secondary channels (link canals, main canals, branch canals and main drains) and employs both mechanical and manual means of weed control. The mechanical control involves the use of hydraulic excavators (Plate 2.2) to remove silt and weed from the channels whilst the manual control comprises the clearance of weeds and some silt with simple hand-tools such as machetes.

The individual farmers on Mwea ISS are obliged to maintain the irrigation and drainage facilities which directly serve their holdings (feeders and field drains, i.e. the quaternary channels). Channel clearance is carried out by hand, as described above. Most farmers require direction from a NIB Field Assistant before they undertake such maintenance work. Farmers are usually instructed to clear their feeders three times per year, prior to land-soaking, transplanting and top-dressing operations, and clear their field drains three times per year, before land-soaking, transplanting and pre-harvest draining (i.e. periods when channels must perform efficiently).

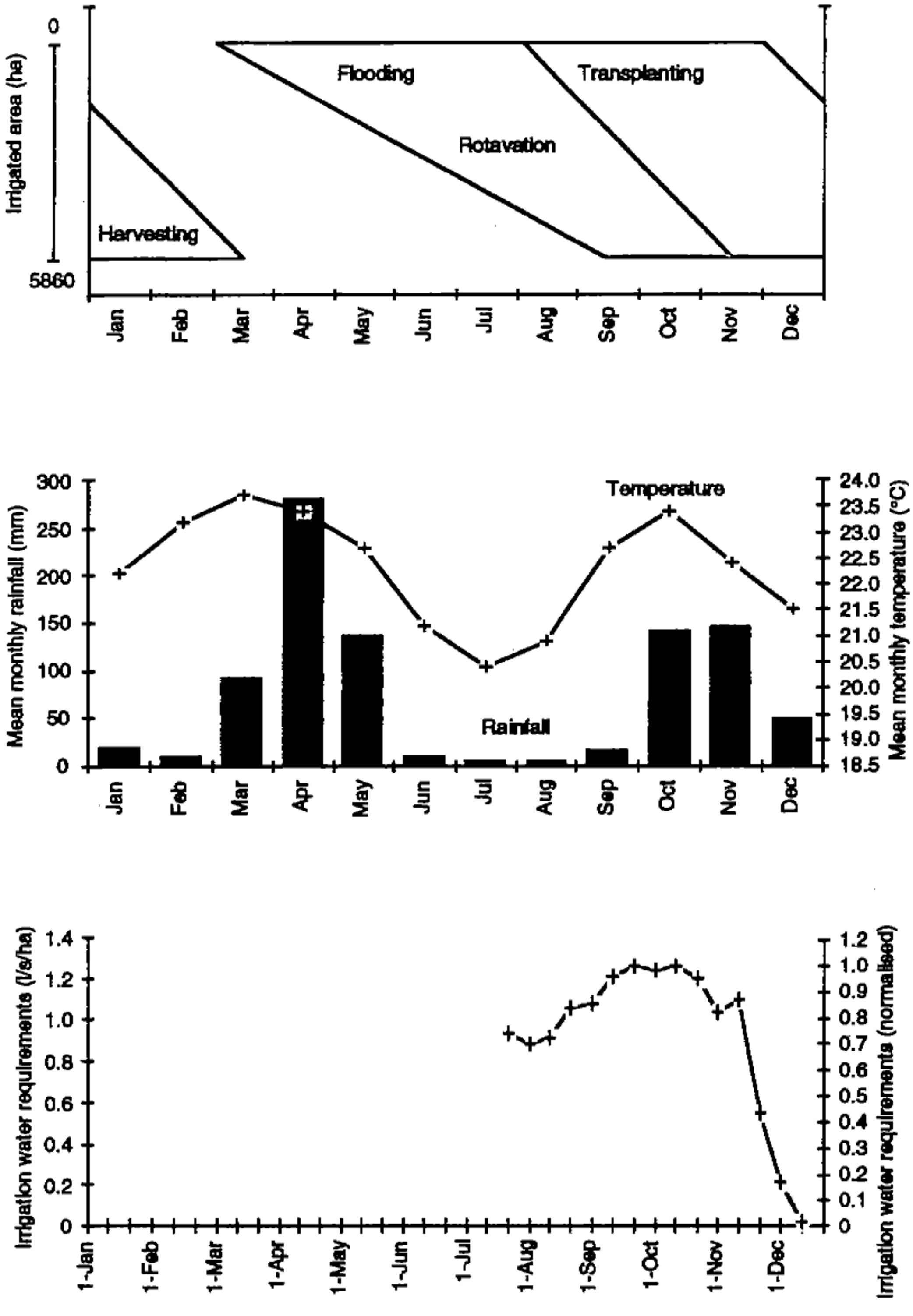

Figure 2.4. Mwea Irrigation Settlement Scheme: (a) Cropping schedule, (b) Mean monthly rainfall and temperature, and (c) Irrigation water requirements

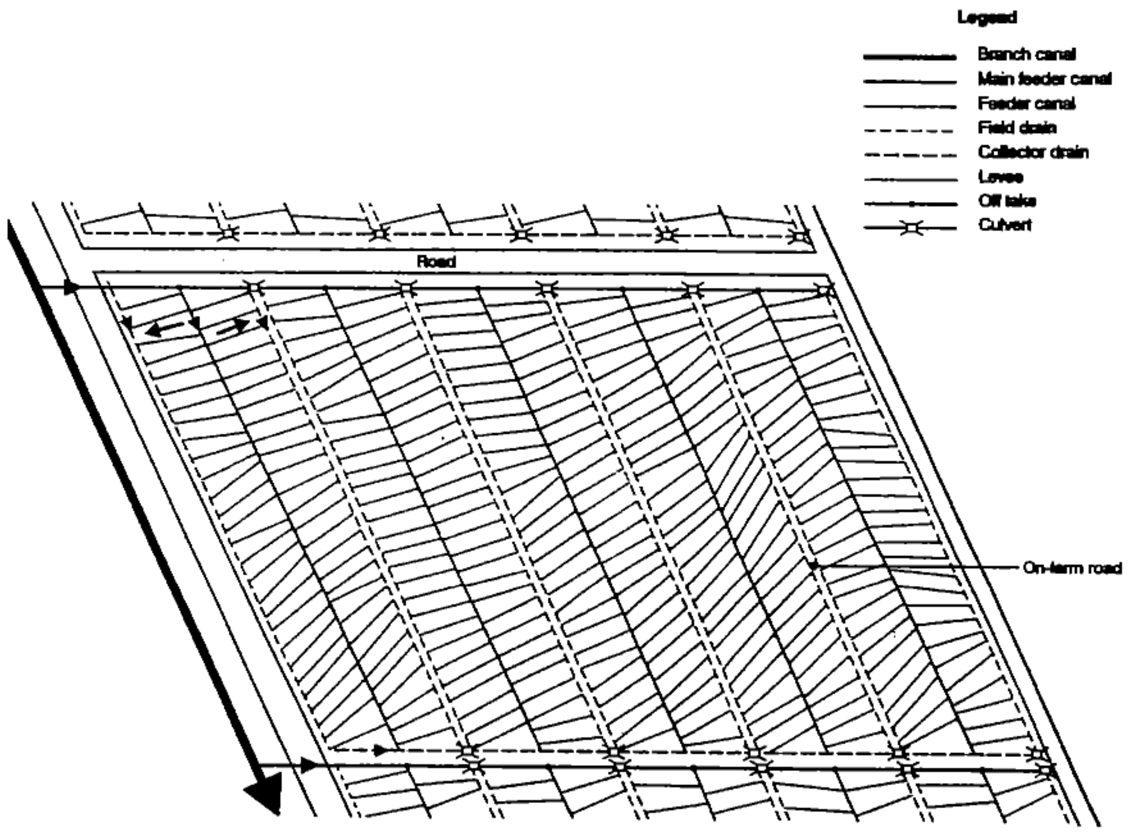

Figure 2.5. Detail of channels in a section of the Mwea Irrigation Settlement Scheme

The management of weeds in main or unit feeders and collector drains at Mwea ISS is undertaken, in part, by both the Works Department and the farmers. The Works Department generally shoulders the responsibility when the channels have accumulated large volumes of silt which require removal. Management on the part of farmers involves a communal effort by those individuals served by a particular watercourse. Ordinarily, main or unit feeders are cleared on two occasions during the crop production season, and collector drains are maintained twice, in preparation for the long rains in March/April and the short rains and pre-harvest draining in November/December (Figure 2.4).

The Works Department's weed management programme is largely dictated by the cropping calendar (specifically the requirement for water in the fields) and the available resources of labour and hydraulic machinery. The Department recognises periods in the cropping calendar when the irrigation system and the drainage system respectively must perform efficiently and therefore aims to maintain the particular system in advance of such critical periods. During non-critical periods, maintenance of a particular system assumes secondary importance.

Between December and March the rice fields are dry, and, following harvest in December to mid-March, are free from any crop. Consequently any 'in-field' maintenance which requires machinery is carried out at this time so that plant can pass freely through the fields. During the same period management of the irrigation system commences with the primary canals and those canals serving the fields which are to be rotavated by tractor early in the year. Drainage is not an important function at this time; however, major drains are excavated during this period in preparation for the long rains in March/April. Ideally, this activity occurs in January/February so that the vegetation partially recovers before the rains arrive and can provide bank protection.

With the arrival of the long rains in March/April, resources are re-directed to drainage maintenance to prevent water-logging (and bogging down of tractors) in the fields, and to prevent water from over-topping drains and flooding in-field roads thereby restricting vehicular access.

Irrigation system maintenance recommences in May/June, canals being cleared systematically in advance of irrigation and rotavation of the fields they serve. September and October represent a critical period for water management. The demand for water at the field level is high since all the fields are under crop and high temperatures cause considerable evapo-transpiration (Figure 2.4). Coincidentally, river flows are at their lowest during this period. Thus, it is imperative that the irrigation system has been maintained and is performing efficiently by this time.

During the period September-November the focus of the maintenance program reverts to the drainage system in preparation for the short rains in October/November and for the pre-harvesting drying-off period (Figure 2.4). At this time main drains are maintained and flood protection works are carried out in the river channels.

The Works Department's management of weeds in irrigation and drainage channels is not confined to mechanical excavation. The recovery rate of vegetation is very rapid. Consequently, in order to sustain channel efficiency, the Works Department is required to deploy maintenance gangs to clear weeds from the channels by hand. Ordinarily, this occurs two or three times per year, usually prior to, or during critical periods for channel function, i.e. between June and October for canals and in March/April and October/November for drains.

2.3.4 Gem Rae Irrigation Scheme, Kenya

2.3.4.1 Physical environment

Gem Rae Irrigation Scheme (hence referred to as Gem Rae) is a small-scale, farmer-managed scheme located in Nyanza Province, approximately 30 km from Kisumu (Figure 2.2). Situated in the Awach Kano Delta area (a former swampland) Gem Rae is in close proximity to three other schemes - Kopudo, Nyachoda and Awach - all of which use the Awach River as their water source.

Although rice cultivation using simple check structures and flood irrigation has occurred in the area since 1938, formal irrigation at Gem Rae did not commence until 1986. The present scheme covers an irrigated area of 90 ha with 270 plots and approximately 230 land-owners (Hide 1994). A further 28 ha is occupied by farmers on the margins of the scheme utilising excess water from Gem Rae and flow in the Awach River downstream from the offtake to Gem Rae.

Most of Gem Rae is underlain by medium to heavy, dark-grey or black clays. Other soils include black cotton clays and medium to heavy clays suitable for rice production due to their impermeability. Annual precipitation in the area is 1,250 mm peaking in April and November, the time of the 'long' and 'short rains' respectively. Temperatures are fairly constant throughout the year, monthly average maxima ranging from 25-35°C and minima between 15°C and 19°C.

Gem Rae is used exclusively to produce a single rice crop per year. Nominally, land preparation commences in June and the grain harvested in December, but in practice, the production season is usually late to start. For the remainder of the year farmers grow maize and sorghum under rain-fed conditions outside the scheme.

Gillott (1994) describes the consequences of the deferred agricultural calendar namely that irrigation often continues through April, contrary to the intended schedule. Heavy rains at this time contribute to high flows in rivers, allowing them to transport heavy concentrations of sediment. Thus, irrigation in April at Gem Rae introduces large volumes of sediment into the scheme which exacerbates the problem of cleaning canals. As a consequence, canal cleaning takes longer and may further delay the onset of cultivation in the following season.

2.3.4.2 Irrigation and drainage systems

The design and construction of the present irrigation scheme at Gem Rae was funded by the Kenyan and Dutch governments. The irrigation system consists of a main canal, three secondary canals and nine tertiary canals. The design cross-section of the main canal is constant along its 2.4 km length with a bed-width of 1.5 m and a side-slope of 1:1.5, however, sections of the canal have become considerably reduced in size as a result of siltation and weed growth. The tertiary canals are approximately 200 m apart and each serves 3-15 ha. The flow of water is continuous to all tertiary canals. Water distribution is achieved by proportional division boxes constructed from concrete blocks. No provision is made for manual control of the water.

Basin irrigation is the exclusive practice at Gem Rae. Each plot is divided into basins which vary in size from 100-2500 m^2. Following abstraction from the tertiary canals, irrigation water passes from basin to basin through depressions in the bunds on a 24 hour basis.

No formal drainage system exists at Gem Rae because of a reluctance on the part of farmers to excavate and maintain the channels.

The operation and management of Gem Rae is conducted by the Scheme Committee with advice from the local extension officer. The Committee is comprised of 24 members who convene at the beginning and end of the production season. Although the Committee is supposed to play a directoral role at Gem Rae, its administrative capacity is weakened by the fact that it has no powers to enforce scheme rules. Furthermore, a recent study (Hide 1994) noted that, contrary to outward impressions, the Scheme Committee was beset by internal disputes and did not function correctly. At a lower level of organisation farmers are divided into groups sharing a common tertiary canal.

2.3.4.3 Aquatic weed management

The control of weeds in the irrigation system at Gem Rae is a secondary benefit of maintenance activities directed at accumulated sediments rather than a specific management priority. The responsibility for maintenance of the main and secondary canals at Gem Rae rests with the entire scheme under the direction of the Scheme Committee. The tertiary canals should be maintained by the farmers. Hide(1994) suggests a major drawback to the system employed at Gem Rae arises because individual farmers are responsible for the section of tertiary canal adjacent to their plot which provides the individual farmer with a strong disincentive to clear the canal until farmers upstream have completed their sections. Hide (1994) concludes that the lack of co-operation between farmers and poor leadership from the Scheme Committee, in addition to the deposition of large amounts of sediment in the canals are leading to a downward spiral in the operation of the scheme.

2.3.5 Welland and Deepings Internal Drainage Board

Extensive areas of the United Kingdom have a high dependency on complex networks of flood defences and drainage systems. Within England and Wales, such areas of dependency invariably fall within drainage districts where protection from the sea and the management and evacuation, as necessary, of inland water combine to provide conditions within which land use can be sustained. The principal organisations charged with maintaining adequate standards of flood protection and land drainage within drainage districts in England and Wales are the Environment Agency and Internal Drainage Boards such as Welland and Deepings Internal Drainage Board.

Welland and Deepings Internal Drainage Board is responsible for a drainage district covering 32,415 ha in Lincolnshire, eastern England. The total length of drains maintained in the district is approximately 670 km.

The Board's aquatic plant management practices are capital intensive, based on sophisticated weed-cutting machinery, including a weed-cutting launch, a 'Bicycle' tractor, a 'Spider' tractor, and land based excavators and tractors equipped with weed-cutting buckets. Such equipment demands a heavy investment in terms of maintenance and, in this respect, the Board is self-contained, having its own workshop and three mechanical fitters.

The maintenance programme is based on experience, developed traditions and available finances. Most of the drainage network is maintained at fixed times in the year, with fixed frequencies and fixed techniques. The weed-cutting machinery is deployed in May and remains in operation until December. During this period, each channel is cleared of vegetation at least twice; some are cleared three times. The programme is revised occasionally if access to a channel is restricted because land is under crop.

The selection of weed-cutting machinery is largely determined by the dimensions of the drainage channels and access to the watercourses. To maximise efficiency, it is usual for machinery to follow a similar route around the drainage district each year, and each machine is normally driven by the same driver.

During the winter months (January to April), the mechanical excavators are employed in channel dredging operations which are carried out on a five year cycle. The multi-functional use of heavy plant is important to recuperate costs. The other weed-cutting machinery is overhauled during these months.

In the past, the primary management concern of Internal Drainage Boards was to maintain channels for water conveyance. Hence, complete channels were cleared of vegetation. In recent years, however, internal drainage boards, under pressure from conservation lobbies and as a result of environmental legislation, have been forced to recognise the value of their systems for nature conservation and adapt their management practices accordingly. This has prompted a general move away from herbicides towards mechanical techniques. Drainage engineers are encouraged to exercise caution towards their weed-cutting practices, and leave half-channels or single banks uncut to provide for wildlife.

Conditions which prevail at Welland and Deepings Internal Drainage Board are very different from those in say, Zimbabwe or Kenya. A lack of foreign exchange and technical expertise in Africa generally prohibits use of the specialist equipment currently operated by the Board, although large state-owned or commercially managed irrigation projects in Africa may be an exception to this rule. The feeling amongst staff at Welland and Deepings Internal Drainage Board is that the technology employed by the Board in the 1960's (manual techniques and self-propelled pedestrian machines) is perhaps more transferable to the developing world.

Welland and Deepings Internal Drainage Board maintains detailed records of the costs of aquatic plant management practices. These have been used as a basis to develop a methodology for financial and economic comparison of different methods of control.

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Plate 2.1 Use of tools for manual aquatic weed control: (a) slasher, (b) and (d) sickle, Chisumbanje Estate, Zimbabwe; and (c) hoeing, Mwea Irrigation Settlement Scheme.

Plate 2.2 Mechanical attachments for aquatic weed control: (a) dredger bucket, (b) weed cutting backet with reciprocating cutter blades; (c) tractor mounted flail mower.

Plate 2.3 Shading using trees, Hadejia Jama'are River Basin Irrigation Scheme, Nigeria

CHAPTER 3

IDENTIFICATION AND DIAGNOSIS OF WEED PROBLEMS IN IRRIGATION AND DRAINAGE SYSTEMS

3.1 Introduction

This chapter explains the need for weed management and provides guidelines on identifying and diagnosing weed problems. These are presented by considering the different types of weed in irrigation and drainage systems, the range of weed species, and the ecology of weeds and weed communities. A classification of weed communities is described using analyses from case study sites in Zimbabwe and Kenya. These examples provide a good illustration of both the different types of channels, in terms of aquatic weed flora, which make up the channel network, and the change, or development, of the aquatic flora in a given channel over time. The aquatic weed flora of such irrigations systems is made up of around 40 - 60 different species of which about 30% are likely to be either in need of management or useful indicators of a particular channel type. The various detrimental effects of weeds are then described, followed by a concluding section on recording the condition of irrigation and drainage channels.

3.2 Definition of a weed

The term weed refers to a plant which is not desired at its place of occurrence (Coördinatieconommisse Onkruidonderzoek 1984). It may equally be applied to terrestrial (land) and aquatic (water) plants. In terrestrial habitats, weeds are easily recognised because they usually compete with crops or ornamental plants. The multi-functional use of many aquatic habitats, however, complicates the assessment of the 'weediness' of plants which may interfere with one use, such as irrigation, while promoting another, such as fish production (Mitchell 1985). Nevertheless, in an aquatic habitat, a plant which interferes, in any way, with the use of water, or constitutes a nuisance to mankind or hazard to human welfare may reasonably be regarded as a weed.

In the context of these guidelines, the term weed is used to refer to any seed-bearing plant, fern, moss or large alga (i.e. visible to the human eye), which affects the performance of irrigation and drainage systems with respect to water delivery.

3.3 Types of weeds

The distinction between aquatic weeds and terrestrial weeds is difficult to determine because there is usually a gradual transition from the aquatic to the terrestrial habitat. Since these guidelines are concerned with the management of weeds which interfere with irrigation and drainage performance, including the channel bank and wholly or partially submerged plants, a broad definition of an aquatic weed is most appropriate. A weed is recognised as being aquatic if it is usually found by or in aquatic habitats and rarely occurs elsewhere (Gibbs-Russell 1977). Hence, most of the weeds which cause nuisance in irrigation and drainage systems are aquatic weeds. Those weeds growing on the channel bank away from the influence of the water are described as bankside weeds. In addition to aquatic weeds, these plants are also referred to as aquatic plants or aquatic vegetation.

Aquatic weeds may be categorised into four separate types based on the habit of their growth:

- submerged weeds;
- free-floating weeds;
- floating-leaved weeds (rooted to the channel bottom; and
- emergent weeds.

Examples of the four main weed types are illustrated in Plate 3.1.

3.3.1 Submerged weeds

Submerged weeds are those that spend their entire life cycle, with the possible exception of flowering, beneath the surface of the water. They are usually anchored to the bed of the water body and are completely submerged. Some submerged weeds such as *Ceratophyllum* species, however, are not rooted to one place and many submerged species bear their flowers above the water surface. Examples of submerged weeds include *Najas* species and some members of the genus *Potamogeton*.

3.3.2 Free-floating weeds

Free-floating weeds drift on the water surface. Most of the plant body is carried above the water surface including the flowers, and the roots, if present, hang free in the water. Examples of free-floating weeds are *Eichhornia* species, *Pistia stratiotes* and *Azolla* species.

3.3.3 Floating-leaved weeds

Floating-leaved weeds produce leaves which float on the water surface but their roots are anchored to the bed of the water body. Some submerged leaves are often present and the flowers usually emerge from the water surface. Examples of floating-leaved weeds include *Nuphar* species, *Nymphaea* species and some members of the genus *Potamogeton*.

3.3.4 Emergent weeds

Emergent weeds are those whose roots and basal portions develop beneath the water surface but whose stems and leaves are borne primarily in the air. Emergent weeds commonly occur along the margins and shores of water bodies and in swamps and marshes. Typical emergent weeds include *Typha* species, *Phragmites* species and *Cyperus* species.

These are useful categories into which aquatic plants can be separated. In reality, the distinctions between them can be unclear and some species exhibit more than one form even in the same plant. For example, some *Potamogeton* species have both floating and submerged leaves.

3.4 Weed species in irrigation and drainage systems

Irrigation and drainage channels and night-storage reservoirs support a range of aquatic weeds. Species recorded in irrigation and drainage systems in Africa are listed in Appendix 1. Some of these weeds are more problematic than others and these can be divided into two groups (Mitchell 1985):

- species indigenous to Africa which thrive in aquatic habitats created or disturbed by humankind (e.g. artificial waterbodies such as canals or drains and waters enriched by nutrients derived from human activity); and
- non-indigenous species which are able to fully exploit aquatic habitats because of the absence of limiting environmental factors present in their native environments.

Typically, populations of the weeds listed in Appendix 1 are able to reproduce very quickly and are very difficult or very expensive to control. Whilst such noxious weeds may not necessarily establish themselves in all irrigation and drainage systems, irrigation managers should provide for vigilant surveys to identify potential problems at an early stage.

Several species of aquatic weed which occur in irrigation and drainage systems, although detrimental to system performance (Appendix 1), are potentially of value to local economies as:

- food resources for humans, for livestock and for fish production;
- soil additives, including green manure, mulch and compost;
- resources for pulp, paper and fibre production for building and weaving;
- resources for energy production.

Appendix 1 summarises the ways in which aquatic weeds in irrigation and drainage channels and night-storage reservoirs may be utilised.

3.5 Weed ecology

The status of an aquatic weed within a given habitat is the reflection of an integrated response by the weed to physical, chemical and biological factors prevailing in that habitat. Submerged, free-floating, floating-leaved and emergent weeds encounter different environmental conditions and exhibit a range of adaptations which determine community structure (assemblage of weeds) in a given aquatic habitat.

The environmental factors which may be significant to weed growth in irrigation and drainage systems in the tropics and sub-tropics are:

- physical factors:
- water availability and water movement;
- substrate;
- light;
- temperature;
- chemical factors:
- nutrient status;
- pH;
- biological factors.

3.5.1 Physical factors

3.5.1.1 Water availability and water movement

By definition, aquatic weeds require an abundant supply of water. Emergent weeds are usually able to tolerate dry periods, but the leaves of floating and submerged weeds normally die quickly if dried. Short periods of drought tend not to affect roots or rhizomes (underground stems) growing in the substrate (material in which weeds are rooted) and, from these, weeds are able to regenerate quickly once the water returns. Prolonged drought is more damaging to weeds, and new growth must come from deep roots and rhizomes or seeds which have survived buried in the substrate (e.g. the canal bank), or from outside the community (Haslam 1978).

By minimising the incidence of significant drought events, irrigation and drainage channels and night-storage reservoirs provide favourable habitats for aquatic weeds. Many irrigation systems are operated year-round so the irrigation channels and night-storage reservoirs are provided with an almost perennial supply of water. Such water bodies are able to support submerged, free-floating, floating-leaved and emergent weeds. Drainage channels, in which water flow tends to be more ephemeral, are characterised by more drought-resistant emergent weeds.

Aquatic weed distribution and abundance is also affected by water depth. Shallow water is often detrimental to submerged weeds, inciting poor growth, even though the plant shoots are in water and have space for development (Haslam 1978). Tall emergent weeds such as *Phragmites australis* may also be limited by water depth. At the other extreme, few emergent weeds are able to live submerged in the water because they cannot photosynthesize.

One of the most important factors influencing the plants which occur in aquatic habitats is water movement. Compared with the wide range of flow velocities which occurs in natural watercourses, the regulated flows in irrigation canals are relatively uniform. Flow rates (which seldom exceed 1.8m/s (Chow 1983)) are generally too low to cause physical damage to weeds through turbulence or spate (Butcher 1933; Haslam 1978). However, the development of some free-floating, floating-leaved and emergent weeds in primary/secondary canals may be inhibited by the rate of water movement. Many weed species commonly associated with irrigation canals (e.g. *Potamogeton* species) are typified by a preference for low water velocities (Haslam 1978); other species, more tolerant of faster flows and increased turbulence, sometimes occur in short lengths of canal immediately downstream of off-takes, flumes or weirs.

3.5.1.2 Substrate

The growth of aquatic weeds is influenced by the physical texture and chemical composition of the substrate. The physical properties of a substrate are the product of the bedrock, erosion by water turbulence and currents, elutriation (separation by water) of the lighter and heavier eroded particles, deposition of inorganic and organic sediments and the activities of flora (plants) and fauna (animals) (Sculthorpe 1967). The processes of erosion and elutriation create graded substrates in which there is an overall decrease in particle size with decreasing water turbulence and velocity. Generally speaking, finer substrates that contain a high proportion of silt particles tend to be richer in nutrients than coarse substrates since most nutrients are bound to the silt particles (Haslam 1978).

Some aquatic plants are most abundant on fine substrates, others grow best on coarse substrates. The situation arises because aquatic plants exhibit a preference for a particular substrate, a preference for a particular type of water movement, or a preference for the combined effect of flow and substrate (Haslam 1978).

The beds of unlined irrigation and drainage channels are usually dominated by fine substrates. In reaches immediately downstream of off-takes, flumes or weirs, where water velocity and turbulence are locally increased, coarser substrates may be found.

The substrates occurring on the beds of night-storage reservoirs sometimes exhibit a depth-related gradation, coarser substrates occurring along the shore-line where wave-induced turbulence is greatest.

3.5.1.3 Light

All green plants are dependent on light as an energy source for photosynthesis. Light can be a limiting factor for aquatic weed growth, particularly for submerged species. Light availability and quality in water are influenced by the angle of incidence of sunlight, water surface reflectivity, shade, and attenuation due to absorbance by water molecules, dissolved and suspended substances and plant and animal tissues (plankton) in the water (Sculthorpe 1967; Haslam 1978). The actual depth at which limiting light intensity is reached is a function of these factors and varies from site to site.

High suspended sediment loads are a characteristic feature of many irrigation schemes in the tropics and sub-tropics and may limit weed growth in some of the larger, deeper irrigation canals, by contributing to a reduction in light availability.

Trees, shrubs and other tall vegetation along the channel or reservoir margin will reduce light availability. Bottom feeding fish can create turbidity by stirring up the substrate and hence reducing light penetration.

3.5.1.4 Temperature

Plant growth is usually limited by temperatures of less than 6-7ºC. Temperature fluctuations in aquatic habitats are generally much less extreme than in the aerial environment. Seasonal and daily fluctuations of temperature in flowing waters are greatest in summer and/or at lower altitudes where air temperatures fluctuate more and where there is an influx of surface water affected by local weather conditions (Sculthorpe 1967). At any one location, however, water temperature fluctuations are usually moderated by turbulence and the diurnal amplitude may be reduced to as little as 1°C.

In the tropics and sub-tropics, air temperatures remain relatively high throughout the year. Coupled with the relatively slow and uniform water movement in irrigation and drainage channels, this results in relatively high water temperatures which promote vigorous plant growth year-round.

The rapid rate of weed growth which occurs in irrigation and drainage channels at Mwea Irrigation Settlement is illustrated in Plate 3.2. Vegetation recovers very quickly following channel maintenance. In the smaller, tertiary and quaternary channels (unit feeders, feeders, field drains and collector drains), vegetation cover, following manual cutting, was observed to increase from zero to 100 percent within 2-3 months. In the primary and secondary canals, the rate of recovery was somewhat slower: after dredging, weed cover increased from zero to 90 percent within 5-6 months.

The differences in the rates of vegetation recovery in primary/secondary channels and tertiary/quaternary channels may partly be explained by reference to the maintenance carried out on the channels. Dredging usually has a greater impact on vegetation than manual cutting since roots and rhizomes are removed in addition to the stems and leaves. Furthermore, primary/secondary irrigation canals are relatively less favourable habitats for weed communities than tertiary/quaternary canals and drains because higher water velocity, greater water depth and reduced light availability may inhibit the growth of certain weed types.

3.5.2 Chemical factors

3.5.2.1 Nutrient status

Sixteen nutrients are known to be essential to plant growth (Riemer 1984). These can be divided into macronutrients (carbon, hydrogen, oxygen, nitrogen, phosphorus, sulphur, potassium, calcium and magnesium) and micronutrients (iron, manganese, boron, zinc, copper, molybdenum and chlorine) according to the relative amounts in which they are required by plants. Free-floating species necessarily obtain nutrients from water alone. Other aquatic weeds may derive nutrients from the water and/or the substrate in which they are rooted. The relative importance of the nutrient sources is uncertain but probably varies between species (Haslam 1978).

The nutrient content of the water and substrates in an aquatic habitat reflects the catchment geology and fertility (which is greatly affected by land use). The specific concentration and relative proportion of nutrients available for plant growth in any one habitat are extremely variable. Causes of variation include precipitation and evaporation, activities of animals, e.g. livestock, the substrate chemistry and pollution.

Little is known of the biological roles of the micronutrients in aquatic habitats. It is generally assumed that they are present in sufficient quantities in most waters so that plant growth is rarely limited by any of them. Of the macronutrients, comparisons of plant tissue and freshwater nutrient concentrations suggest that for aquatic weeds generally, nitrogen and phosphorus are most likely to limit plant growth under natural conditions (Raven 1984). These substances are frequently applied to fields on irrigation schemes to boost crop production. If they are leached from the soil into drains and canals (via recirculation of drainage water), they may enhance aquatic weed growth. Nitrogen and phosphorous are often implicated in the acceleration of eutrophication (nutrient enrichment) of waters by human activity.

Submerged plant growth may also be limited by carbon and, under conditions of high biological oxygen demand (e.g. following organic pollution), by oxygen. Unlike free-floating, floating-leaved and emergent weeds which derive carbon and oxygen from free carbon dioxide and oxygen in the atmosphere, submerged plants must obtain these nutrients from the water. Carbon is available to submerged plants in the form of dissolved carbon dioxide or bicarbonate ions; oxygen exists only as dissolved gas in the water.

When nutrients are absorbed by plants, the area immediately surrounding the site of uptake (e.g. the water around each leaf) is depleted of nutrients and a diffusion gradient is established between the impoverished area and the surrounding water. In still waters particularly, the rates of diffusion of dissolved gases, other nutrients and waste products can be so slow that the demand for nutrients by submerged plants is not met and plant growth is limited (Sculthorpe 1967). Water movement (turbulence and currents) assists the dissolution of atmospheric gases and increases diffusion gradients, facilitating the exchange of substances between the water and the plants (Westlake 1967). The flow of water in canals and drains, therefore, constantly replenishes dissolved gas and nutrient supplies, and submerged weed growth is probably not limited by nutrient availability.

3.5.2.2 pH

The pH of freshwaters varies from acid to alkaline (usually from pH 6 to pH 9) and is modulated by hydrogen and hydroxide ions. The pH of water has direct and indirect effects on the photosynthesis and growth of submerged weeds, affecting the active uptake of nutrients by plants, and affecting the form and availability of nutrients such as phosphorus, nitrogen and carbon, respectively. Photosynthesis and therefore weed growth generally declines as pH increases.

3.5.3 Biological factors

3.5.3.1 Interactions between living organisms

The composition of plant communities in irrigation and drainage channels, whilst partly determined by physical and chemical factors, is also a reflection of interactions which occur between plants and animals living in the channels. The relative rates of plant growth and competition between plants of similar or different life form are particularly important in this respect (Sculthorpe 1967). More vigorously growing species tend to have a competitive advantage over less active species. Competition occurs when two different species contend for the same environmental resource. In competing for a resource, one species may make a habitat less suitable for another, e.g. emergents and/or floating species in the water column may shade plants below. Species which are in competition with each other are typically unable to persist together for an indefinite period. Insects and other invertebrates can also have a significant effect, usually on one species in a community, by either eating the leaves or damaging, for example, the stem or flower buds.

The interactions between aquatic weeds and the aquatic animals they support are numerous. However, the impact of grazing animals is perhaps the most important in terms of aquatic plant community composition. Domestic animals such as sheep and cows often roam freely on irrigation schemes in the tropics and sub-tropics. The effects of their grazing can be quite marked in localised areas.

Weeds are susceptible to diseases, e.g. fungal, but very little is known about this factor.

3.5.3.2 Human activities

Perhaps the greatest influence on the distribution and abundance of plant communities in irrigation and drainage channels derives from human activities, particularly attempts to control weed growth. Whilst clearly reducing the standing crop of aquatic weeds, cutting, dredging or herbiciding (see Chapter 4) may also alter the composition of plant communities by excluding certain species and encouraging the growth of others. The impact of weed control activities on the aquatic flora in irrigation and drainage ditches is usually proportional to the severity of the treatment in relation to water availability after maintenance.

3.6 Community ecology

The structure of weed communities, i.e. the assemblage of different aquatic weed species, in freshwater habitats changes both in space and time.

3.6.1 Spatial variation

The spatial variation in community structure in irrigation and drainage channels can be considered at the small and large scale.

3.6.1.1 Zonation

At the small scale, there is a zonation of life forms across a channel determined by bank slope and depth gradient (Figure 3.1). Characteristically, the sequence is marked by submerged communities in deeper water giving way nearer the shore to a zone of floating-leaved plants. These are replaced by emergent communities in the marginal zone from a water depth of one metre to wet soil on the shore.

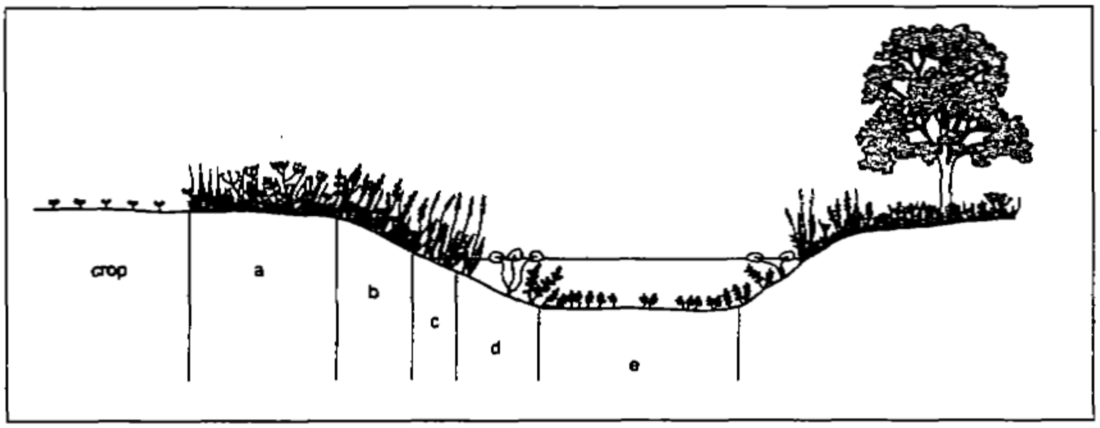

Figure 3.1. Zonation of vegetation in an irrigation or drainage channel ((a) the field margin usually dominated by grasses, with or without trees and, or shrubs; (b) the bank or batter supporting a range of grasses and herbs typically related to water-table; (c) the boundary between land and water with a range of amphibious grasses and herbs able to tolerate variations in water level; (d) the littoral zone in which emergent species occupy the shallower water with floating and submerged species being able to extend into the deeper water; (e) the deep water zone only found in the larger channels supporting mainly submerged plant species)

3.6.1.1 Channel types

The environmental conditions which prevail in irrigation and drainage channels are sufficiently distinct to encourage the development of characteristic plant communities (Figure 3.2). Typically the channels within the irrigation system can be classified into groups of similar channel types based on the composition of the aquatic weed communities. Each group of channels will require a different type of maintenance. The situation can be illustrated by reference to analyses of botanical data collected at study sites on irrigation and drainage channels at Chisumbanje Estate in Zimbabwe and at Mwea Irrigation Settlement Scheme in Kenya.

a. Chisumbanje Estate, Zimbabwe

• Wet Season

The irrigation and drainage channels at Chisumbanje Estate can be divided into six groups on the basis of the species recorded at sites on the channels during the wet season. The classification is summarised in Table 3.1 and the channels which make up the different groups are illustrated in Plate 3.2.

The small, tertiary canals classified in Group A (wet) are characterised by emergent grasses and the sedge *Schoenoplectus* species. These species are indicative of ephemeral aquatic habitats or damp conditions.

Group B (wet) is made up of small, tertiary canals. The range of species being similar to that in Group A (wet), with many emergent grasses and broad-leaved species though with several species indicative of wetter conditions.

Group C (wet) is dominated by larger, tertiary canals characterised by a range of submerged and emergent weeds, including a large compliment of the species occurring in Groups A and B (wet). Plants such as *Cyperus rotundus*, *Potamogeton* species, *Cyperus articulatus* and *Najas horrida* reflect wetter conditions.

The canals described in Groups A, B and C (wet) are generally irrigated regularly, albeit intermittently, throughout the year. Between irrigations they often retain standing water which tends to be shallowest in the canals in Group A (wet) and deepest in the canals in Group C (wet). The species which characterise the canal groupings reflect this situation: emergent species predominate under conditions in the Group A (wet) canals and submerged species develop in the truly aquatic conditions prevailing in the Group C (wet) canals.

Group D (wet) includes sites along a heavily silted, secondary canal and a site on a large, dry tertiary canal. A wide range of weeds is represented at these sites, including terrestrial species generally associated with the tertiary canal or the berms, emergent species characteristic of damp conditions, and emergent species more indicative of wetter conditions. Submerged species are probably prevented from growing in the secondary canal by high levels of turbidity.

Unlike the canals described in Groups A, B and C (wet), the drainage channels in Group E (wet) function only at peak periods during the wet season. Consequently, they are characterised by a range of terrestrial and emergent weeds. *Typha latifolia* is the only species which reflects the occasional aquatic nature of these channels.

Group F (wet) is exceptional because it contains only one drainage channel site. This site is distinct from those in Group E (wet) since it is located at the tail end of the main drain and functions intermittently throughout the year.

- Dry season

The classification of irrigation and drainage channels at Chisumbanje Estate, based on species recorded in the channels during the dry season, is summarised in Table 3.2. The classification described is broadly similar to that for the wet season except that the channels are divided into seven groups.

Group A (dry) contains one large tertiary canal. It is characterised by emergents commonly associated with damp conditions or irregular inundation and emergents, such as *Typha latifolia* and *Ludwigia stolonifera*

Group B (dry) is made up of large tertiary canals but also includes one secondary canal. These channels support a diverse range of submerged, emergent and terrestrial species. The occurrence of a *Potamogeton* species in this Group suggests that the channels in Group B (dry) are subject to longer periods of inundation than those in Group A (dry).

The channels in Group C (dry) are all small tertiary canals. Emergent species which favour damp conditions and *Nesaea* species which occurs in wet habitats, predominate in these channels. However, the *Potamogeton* species is indicative of standing water in the channels.

The weeds which characterise the large tertiary channels in Group D (dry) are largely terrestrial species or emergents which tolerate infrequent inundation. The occurrence of *Schoenoplectus* species and *Ludwigia stolonifera* in abundance is suggestive of a more permanent aquatic habitat.

Group E (dry) is composed of two sites on a heavily silted, secondary canal and two sites representing small, tertiary canals. The canals in this group are typified by emergent weeds which inhabit a range of habitats from those which are only damp or infrequently inundated to those which remain permanently wet.

Two sites on the main drain and site on a dry, tertiary canal make up Group F (dry). The range of species present indicate that the sites are rarely inundated.

The final group in the classification, Group G (dry), contains only two sites, one on the main drain and the other on a tributary drain. Like the channels, in Group F (dry), these sites are characterised by terrestrial species and emergents characteristic of damp conditions. However, emergent species such as *Typha latifolia*, *Cyperus involucratus* and *Phragmites australis* typify wetter conditions than in Group F (dry).

b. Mwea Irrigation Settlement Scheme (Mwea ISS)

The irrigation and drainage channels at Mwea ISS can be divided into four groups. The classification is summarised in Table 3.3.

Group A comprises seven small, tertiary and quaternary canals and 16 drainage channels, most of which are small, tertiary drains characterised by a range of terrestrial and aquatic weeds. These generally reflect the ephemeral aquatic conditions.

Group B include six drains, seven tertiary and quaternary canals and one larger secondary canal. They support a range aquatic weeds including the submerged species *Najas* species and emergents such as *Centella asiatica*. The former species suggests that these channels are inundated for considerable periods.

Group C is dominated by secondary and tertiary irrigation canals and is characterised by emergents. Emergent species also distinguish the primary canal in Group D.

Although the primary and secondary canals at Mwea flow perennially, few submerged species occur in these canals because of elevated flow rates and high turbidity. Thus, these canals tend to be characterised by aquatic emergents growing along the margins of the channels. The smaller, tertiary canals which are irrigated intermittently but retain considerable standing water for extended periods, provide a suitable habitat for submerged species such as *Ludwigia stolonifera* and *Marsilea* species as well as emergent weeds.

The secondary drains and some of the tertiary drains at Mwea are physically very similar to the tertiary irrigation canals and, in places where the secondary drains serve an affluent function in conveying water from one unit to another unit downstream, they have a similar flow regime to the canals. Consequently, the floras in these irrigation canals and these drainage channels are not dissimilar.

The groups dominated by larger irrigation canals which flow perennially, or are inundated for extended periods, are characterised by emergents and some submerged weeds.

These two case studies illustrate that despite having similar channel profiles, there is a range of significantly different channel types within any given irrigation system as based on the aquatic weed flora. At one extreme, the groups comprising larger, tertiary canals are characterised by emergent and submerged species indicative of perennial water or extended periods of inundation. At the other extreme, the groups composed of drainage channels or dry, irrigation canals are typified by terrestrial and emergent species which reflect the ephemeral nature of the aquatic habitat in these channels. Between the two extremes, are groups dominated by smaller, tertiary canals. These channels support emergent and submerged species characteristic of regular, albeit, intermittent, inundation.

The principal factors governing the condition of the channels are channel size, water availability and the degree of weed management. A large discharge capacity, frequent irrigation and regular maintenance (common to the larger, tertiary canals) upholds the condition of a channel in an early successional stage. Another factor which can account for this variation is the stage of development reached by the aquatic weed flora post-maintenance. This is explained more fully in the next section.

Table 3.1. A classification of irrigation and drainage channels at Chisumbanje Estate, Zimbabwe, based on their aquatic floras in the wet season. (Roman numerals indicate the frequency of a species in a given classification group, where V = 81-100 %; IV = 61-80 %; III = 41-60 %; and II = 21-40 %. For the sake of clarity frequencies of less than 21 % (i.e. I) have been omitted from the table.)

Species	Group A	Group B	Group C	Group D	Group E	Group F
Number of channels in group	4	5	14	4	3	1
Channel width (m)	3.5 - 4	4 - 5	4.2 - 5.8	4.5 - 12.2	8.3 - 12	12
Maximum water depth (m)	0 - 0.5	0 - 0.6	0 - 0.3	0 - 0.8	0	0.6
Bank height (m)	0.6 - 0.75	0.6 - 0.9	0.5 - 0.9	0.7 - 1.6	0.9 - 1	1
Bank slope (°)	15 - 45	20 - 35	25 - 40	25 - 45	20 - 45	25
Conductivity (μs)	0 - 120	0 - 130	0 - 190	0 - 140	0	10
pH	0 - 8.2	0 - 8.6	0 - 9.5	0 - 8.1	0	8.5
Number of taxa	5 - 9	6 - 16	6 - 17	15 - 17	11 - 16	15
Percentage cover	20 - 80	30 - 80	10 - 80	25	75 - 90	-
Echinochloa colona	V	V	IV	III	IV	V
Alternanthera sessilis	V	IV	III	IV		V
Commelina sp.	IV	IV	IV	IV		
Eragrostis sp.	IV		IV	IV	II	
Dichanthium sp.	III	III	IV	II	IV	
Paspalum scrobiculatum	III	II		IV		
Echinochloa jubata	III					
Nesaea sp.	II	V				
Cyperus difformis	II	IV	V	II		
Ludwigia stolonifera	II	III	V	IV		
Rhynchosia sp.	II	II	IV	IV	IV	
Eclipta alba	II	II	II	III		
Dinebra retroflexa	II	II		III	IV	V
Eriochloa sp.	II			IV	II	V
Schoenoplectus sp.	II					
Launaea cornuta	II			IV	IV	
Hemarthria altissima		II	III	III		
Nidorella resedifolia		II	III		IV	
Asteraceae		II	III		II	V
Setaria sp.		II		IV	V	
Euphorbia indica		II		III	II	
Pycreus polystachyos		II				
Typha latifolia			III		II	V
Vernonia glabra			III			
Cyperus rotundus			II			V
Fimbristylis bisumbellatus			II			
Chloris pycnothrix			II			
Potamogeton sp. A			II			
Ischaemum afrum				V	V	V
Phyllanthus maderaspatensis				V	IV	
Cyperus articulatus				V		
Corchorus asplenifolius				III		
Persicaria decipiens				III		

Rottboellia cochinchinensis	II	V	
Cyperus digitatus	II	II	
Phragmites australis	II	II	
Abutilon guineense	II		V
Alysicarpus rugosus	II		
Bidens biternata	II		
Centella asiatica	II		
Digitaria sp.	II		
Dolium sp.	II		
Ludwigia octovalvis	II		
Corchorus olitorius		V	
Euphorbia serpens		IV	V
Sesbania sp.		IV	
Amaranthus hybridus		II	
Euphorbia hirta		II	
Conyza albida		II	
Euphorbia heterophylla		II	
Sporobolus sp.		II	
Cucumis sp.			V
Cyperus involucratus			V
Fimbristylis ferruginea			V
Indigofera parviflora			V
Solanum nigrum			V

Table 3.2. A classification of irrigation and drainage channels at Chisumbanje Estate, Zimbabwe, based on their aquatic floras in the dry season. (Roman numerals indicate the frequency of a species in a given classification group, where V = 81-100 %; IV = 61-80 %; III = 41-60 %; and II = 21-40 %. For the sake of clarity frequencies of less than 21 % (i.e. I) have been omitted from the table.)

Species	Group A	Group B	Group C	Group D	Group E	Group F	Group G
Number of channels in group	1	11	5	2	4	3	2
Channel width (m)	4.5	4.5 - 12	3.9 - 4.8	4.8 - 4.9	3.5 - 12.5	4.5 - 12	10 - 12
Maximum water depth (m)	0.1	0 - 0.5	0 - 0.2	0 - 0.3	0 - 0.4	0 - 0.15	0 - 0.4
Bank height (m)	0.7	0.5 - 1.6	0.55 - 0.9	0.7 - 0.8	0.7 - 1.6	0.8 - 1	1
Bank slope (°)	25	20 - 45	25 - 40	25 - 35	15 - 30	20 - 45	25
Conductivity (µs)	250	0 - 260	0 - 250	0 - 200	0 - 180	0 - 190	0 - 10
pH	7.8	0 - 9.9	0 - 8.4	0 - 8.3	0 - 8	0 - 8.2	0 - 8.2
Number of taxa	11	7 - 21	7 - 11	10 - 12	7 - 17	11 - 20	6 - 11
Percentage cover	90	40 - 70	5 - 50	10 - 60	40 - 70	10 - 95	95
Dichanthium annulatum	V	V	V	V	IV	V	
Ludwigia stolonifera	V	V	II	V	IV		
Asteraceae	V	V					
Rhynchosia holstii	V	III		V	II	V	
Dinebra retroflexa	V	II				II	III
Typha latifolia	V	II					V
Imperata cylindrica	V	II					
Pycreus polystachyos	V						
Ischaemum afrum	V			III	II	IV	
Phyllanthus maderaspatensis	V					II	
Fimbristylis dichotoma	V						
Commelina sp.		V	V		IV	IV	
Echinochloa colona		V	III	V	IV	IV	III
Cyperus difformis		IV	IV	V		II	
Alternanthera sessilis		IV	III	III	IV	II	III

Hemarthria altissima	IV		III			
Nesaea sp.	III	V	III	III		
Eragrostis sp.	III		V	II	IV	
Potamogeton sp. B	III					
Vernonia glabra	II		III		II	
Cyperus articulatus	II			III		
Euphorbia indica	II			II	V	
Sporobolus sp.	II			II	II	
Centella asiatica		II		IV		
Paspalum scrobiculatum		II		III		
Potamogeton sp. A		II				
Setaria sp.			III	III	IV	
Corcorus asplenifolius			III	II	IV	
Eclipta alba			III		II	
Schoenoplectus sp.			III			
Fimbristylis sp.			III			
Eriochloa sp.				III		V
Cyperus digitatus				III		
Persicaria decipiens				III		
Euphorbia hirta				II	IV	
Acmella caulorhiza				II		
Chara sp.				II		
Echinochloa jubata				II		
Ludwigia octovalvis				II		
Najas horrida				II		
Sesbania rogersii					V	III
Launaea cornuta					V	
Bidens biternata					IV	III
Acacia sp.					IV	
Corchorus olitorius					II	V
Abutilon guineense					II	III
Amaranthus hybridus					II	III
Alysicarpus rugosus					II	
Bidens pilosa					II	
Euphorbia heterophylla					II	
Ricinus communis					II	
Cyperus involucratus						III
Euphorbia serpens						III
Phragmites australis						III
Portulaca oleracea						III

Table 3.3. A classification of irrigation and drainage channels at Mwea Irrigation Settlement Scheme, Kenya, based on their aquatic flora. (Roman numerals indicate the frequency of a species in a given classification group, where V = 81-100 %; IV = 61-80 %; III = 41-60 %; and II = 21-40 %. For the sake of clarity frequencies of less than 21 % (i.e. I) have been omitted from the table.)

Species	Group A	Group B	Group C	Group D
Number of channels in group	23	14	14	1
Channel width (m)	0.4 - 8.25	1.4 - 5.0	1.5 - 9.18	9.12
Maximum water depth (m)	0 - 0.73	0.05 - 1.01	0 - 1.32	-
Velocity	0 - 0.74	0.026 - 1.25	0.01 - 1.0	0.71
Number of taxa	6 - 18	1 - 14	5 - 22	9
Percentage cover	2 - 100	1 - 100	10 - 90	25
Leersia hexandra	V	V	V	
Cynodon dactylon	V	II	III	V
Commelina sp.	IV	IV	V	V

Ludwigia stolonifera	IV	II		
Panicum repens	III		IV	
Echinochloa colona	III			
Paspalum scrobiculatum	II	II		V
Rhynchosia sp.	II		III	
Fimbristylis sp.	II		II	
Alternanthera sessilis	II			V
Ageratum conyzoides	II			
Ajuga remota	II			
Asystasia sp.	II			
Bothriochloa insculptum	II			
Cyperus sp.	II			
Dyschoriste sp.	II			
Indigofera sp.	II			
Marsilea sp.	II			
Oryza sativa	II			
Euphorbia hirta	II			
Ottelia exerta	II			
Acmella caulorhiza		II	III	V
Eclipta alba		II	III	
Centella asiatica		II		
Najas sp.		II		
Polygonum senegalense			III	V
Cyperus latifolius			III	
Ludwigia abyssinica			III	
Sphaeranthus sp.			III	
Cyperus dives			II	V
Echinochloa pyramidalis			II	
Polygonum salicifolium			II	
Pycnostachys deflexifolia			II	
Desmodium sp.				V
Oldenlandia sp.				V
Polygonum sp.				V
Typha latifolia				V

3.6.2 Temporal variation

Temporal changes in community structure which commence in aquatic habitats are known as hydroseral succession. The successional process is dependent upon a raising of the bed of the water body towards the water surface by the accumulation of plant remains and/or silt. As the water body becomes shallower, submerged species in once deeper areas of the habitat may be replaced by floating-leaved species that encroach towards the centre of the water body reducing light availability in the water column. Emergent species similarly extend further and further from the original shoreline until the open water disappears.

The stages of the hydroseral succession which occur in irrigation and drainage channels at Mwea Irrigation Settlement Scheme in Kenya are illustrated in Figure 3.2. They are more fully described as follows:

'open water' - the channel banks above the mean water level are vegetated with terrestrial and aquatic weeds including grasses such as *Bothriochloa insculptum* and *Cynodon dactylon*, herbs such as *Amaranthus spinosa* and *Oxygonum sinuatum*, and shrubs such as *Abutilon* species, *Ricinus communis*, *Cassia didymobotrya* and *Sida* species (These species are present throughout the latter stages of the succession described below). The wetted perimeter of the channel at the open water stage is free from vegetation.

'submerged and/or free-floating weeds' - the channel banks are vegetated as described above, but the wetted perimeter is also colonised by submerged weeds such as *Najas* species. Free-floating weeds such as *Lemna* species may, or may not, be present. The submerged and/or free-floating stage is more characteristic of primary and secondary canals with perennial water supply than in tertiary canals and drains with intermittent flow.

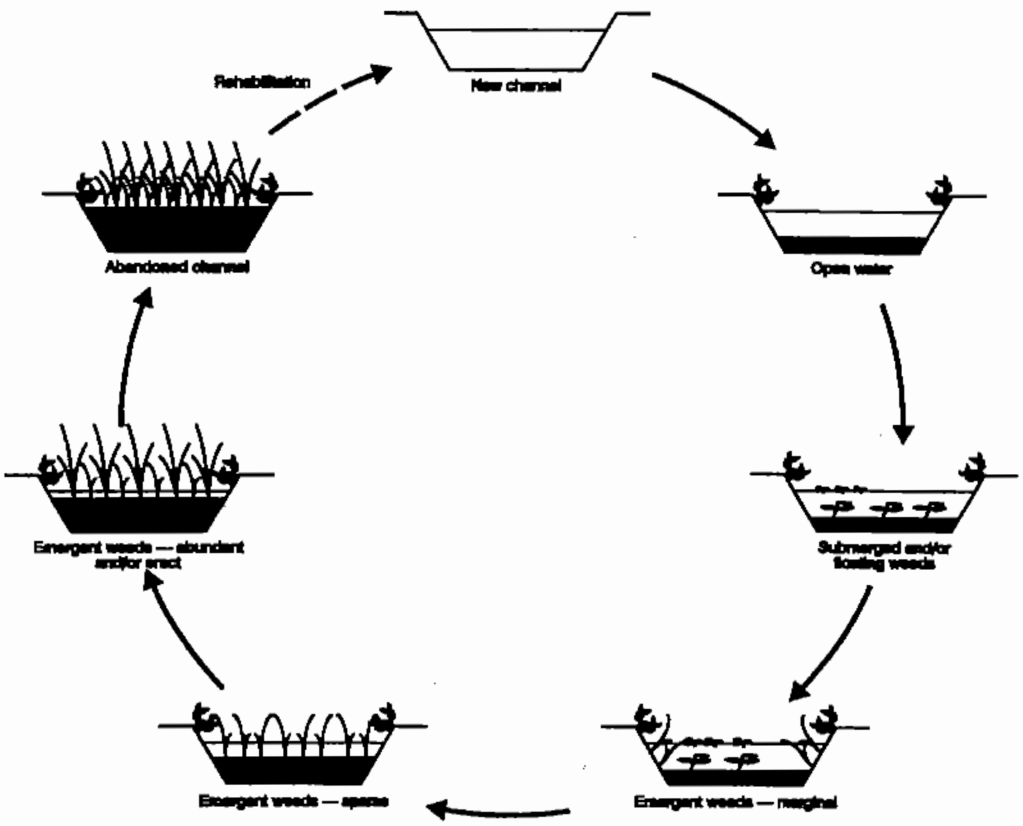

Figure 3.2. The stages of the hydroseral succession which occur in irrigation and drainage channels at Mwea Irrigation Settlement Scheme, Kenya

'marginal emergent weeds' - emergent grasses (e.g. *Echinochloa* species and *Leersia* species), sedges (*Cyperus dives* and *Cyperus latifolius*) and herbs (e.g. *Commelina* species and *Sphaeranthus* species) occur along the water margins and encroach towards the centre of the channel. The banks are vegetated as before, but the submerged and/or free-floating weeds may, or may not, be present.

'sparse emergent weeds' - emergent vegetation covers the entire bed of the channel, often excluding submerged vegetation. Certain emergent weeds such as the herb *Ludwigia stolonifera* and the grass *Leersia* species invade the channel from the water margins; others such as the sedge *Cyperus articulatus* and the floating-leaved herb *Marsilea* species develop in the centre of the channel.

'abundant and/or emergent weeds' - emergent vegetation covers the entire bed of the channel as in the previous stage; however, the species occurring at this stage tend to be more abundant, taller and more erect than those in the sparse emergent stage. The presence of *Typha* species and the occurrence of *Cyperus dives* within the wetted perimeter is indicative of channels in the abundant and/or erect stage.

The rate of succession from one stage to the next is dependent on several factors: channel size (width and depth); water velocity; light and temperature regime; the degree and frequency of channel maintenance; the availability of water in the channel and the persistence of the existing weeds.

The successional process tends to be slower in deeper and wider channels. For instance, larger canals (primary and secondary canals) usually exhibit all stages of succession during a single cycle, whereas smaller tertiary and quaternary canals frequently pass from the open water stage directly to one with a high percentage cover of emergent weeds. In some primary and secondary canals, the depth of water combines with water velocity to slow the encroachment of marginal emergent vegetation. The rate of flow in these channels may also be inhibitory to free-floating weeds. Water depth in combination with high turbidity in primary and secondary canals can prevent the growth of submerged weeds.

Hydrological differences between irrigation and drainage channels produce distinctions in the ecology of these channel types. The slower, more intermittent flow in drainage channels generally favours the development of emergent weeds over submerged and free-floating weeds.

3.7 Detrimental effects of weeds in irrigation and drainage systems

Weed problems in irrigation and drainage systems are generally caused by prolific plant growth. In low density, aquatic plants are usually beneficial to the system because they help stabilise the channel banks, improve water quality, and provide habitat for aquatic fauna such as fish (Marshall and Westlake 1978).

The principal adverse effects of large amounts of weed in irrigation and drainage channels are that they:

- interfere with water flow in canals and drains, inhibiting water delivery to the crop and drainage from the fields;
- entrap sediment, causing a progressive reduction in the capacity of a channel or reservoir;
- reduce reservoir capacity by occupying useful volume and increasing water loss through evapotranspiration;
- block pump intakes, interfere with the operation of regulator gates and weirs, and threaten structures such as canal linings and bridges;
- assist the spread of diseases such as schistosomiasis and malaria by reducing flow velocities and providing habitats for the intermediate vectors of the parasites causing these diseases;
- provide a source of weeds which may spread from irrigation and drainage channels into irrigated fields;
- necessitate the draining of canals and reservoirs for weed control, thereby interfering with irrigation schedules; and
- require the utilisation of scarce resources including finance, labour and equipment in order to achieve control.

Adverse effects of secondary importance are:

- weeds alter the flora and fauna by providing new habitats which may support pests such as rats, snakes and insects;
- weeds interfere with fisheries;

- weeds remove nutrients from the water which might otherwise be available to the crop;
- weeds impair the access of domestic animals to drinking water; and
- weeds when they die, degrade water quality by adding taints and odours and reducing the dissolved oxygen content.

3.7.1 Flow resistance

The relationship between vegetation and hydraulic resistance (resistance to water flow) is of considerable importance to watercourse designers and managers. The most commonly used indicator of the reduction in discharge capacity caused by weed growth is Manning's 'roughness co-efficient' (n) derived from the Manning equation:

$$Q = A.R^{0.67}.S^{0.5}/n$$

where: Q is the discharge;

A is the cross-sectional area of flow;

R is the hydraulic radius;

S is the slope of the water surface; and

n is the roughness (retardance) coefficient.

The presence of weed in a channel increases the hydraulic resistance and raises the value of Manning's n above the design specification for the channel. Studies have demonstrated a temporal variation in Manning's n in response to the development of vegetation during the course of the growing season (Vinson *et al.* 1992).

On the Kalabia Canal in Upper Egypt, the design value of Manning's n is 0.025. However, measurements taken over a two-year period in the mid-1980's showed the mean value to be 0.048 (Brabben and Bolton 1988). Assuming that the slope, cross-sectional area and hydraulic radius remain the same, the impact of an increase in Manning's n from 0.025 to 0.058 is a reduction in the discharge by a factor of one half. In irrigation terms, this implies that at peak water demands only 50 percent of the water requirement could be supplied by this canal. A 60 percent reduction in peak discharge capacity has been described for the Port Said Canal in Egypt (Brabben 1989). The direct effects of reduced discharge capacity are inadequate water supplied at the far ends of irrigation canals (Gupta 1987) and an inability of drainage channels to remove water from waterlogged areas (Robson 1986).

The degree of resistance offered by weeds varies from species to species, according to the complexity of the plant stand, the form or shape which is presented to water flow, the flexibility, cross-sectional area and spacing of the stems, and the ratio of the depth of water to the height or length of the weed (Pitlo and Dawson 1990; Bakry 1992). For example, free-floating *Eichhornia crassipes* has been found to raise the value of Manning's n from 0.025 to 0.065 while submerged weeds such as *Potamogeton pectinatus* and *Ceratophyllum demersum* have been reported to increase Manning's n to 0.04 (Khattab and El Gharably 1990). Submerged weeds which cover the entire wetted perimeter of a channel act as a lining material, inducing uniform flow with less shear stress and hence a lower hydraulic resistance than weeds covering the bed of only one side of a channel (Bakry 1992).

3.7.2 Siltation

Weeds in irrigation and drainage channels reduce the mean water velocity and thereby increase the deposition of suspended sediments. Significantly more silt, sand and fine gravel accumulate on vegetated substrate than on non-vegetated substrate (Gregg and Rose 1982). In irrigation and drainage systems, siltation contributes to a reduction in the capacity of reservoirs to store water and a reduction in the discharge capacity of canals and drains (Haque and Rahman 1976). The annual deposition of silt in canals at the Gezira-Managil scheme in Sudan is estimated to be 4.5m^3 per hectare served (Mott McDonald and Partners Ltd. 1990).

3.7.3 Loss of reservoir capacity and evapotranspiration

On a large reservoir, where free-floating weeds are the dominant vegetation, the volume of water displaced by them is generally small relative to the useful capacity of the reservoir. However, in a small reservoir, a significant loss of storage may be caused by weed infestation. In Zimbabwe, for example, the loss of capacity for a small reservoir with a mean depth of 0.5 m, was found to be 12.5 - 30 percent (Brabben and Bolton 1988).

The type of weed in a reservoir influences the operational effect of a loss in capacity. Free-floating weeds and submerged weeds displace a more-or-less fixed volume regardless of the depth of water. Emergent weeds, however, occupy a volume approximately proportional to the depth of water around them (Brabben and Bolton 1988).

Three types of reservoir commonly used in irrigation systems are at particular risk from a loss of capacity as a result of weed growth (Brabben and Bolton 1988):

- local storage ponds or night-storage reservoirs (e.g., in many small-holder schemes in Zimbabwe);
- intermediate storage tanks formed when a single bank canal crosses a tributary stream (e.g., on many small and medium-sized schemes in Sri Lanka); and
- linear storage reservoirs in which canals are purposely over-sized to produce storage (e.g., minor canals in the Sudan Gezira Scheme).

The effect of weeds on the loss of water from open water surfaces through evapotranspiration is not clearly understood. However, evapotranspirative losses from certain weeds, particularly emergent weeds such *Typha latifolia* and *Cyperus rotundus*, have been found to exceed evaporative losses from open water (Brezny *et al.* 1973).

In most canal systems loss of water due to evaporation is believed to be extremely small relative to the total volume conveyed (Brabben and Bolton 1988). By contrast, in shallow reservoirs, evaporative losses can have a considerable effect on the hydrology and even a modest change in the rate of evaporation, caused by weeds, may be significant.

3.7.4 Obstruction and damage to engineering structures

Operational problems arising from the obstruction of gates and intakes are regularly caused by free-floating weeds such as *Eichhornia* species (Gay 1960; NCR-NAS 1975; Brabben and Bolton 1988). Plant material drawn into pumps can obstruct impellers, and the operating mechanism at sluice gates may be jammed by accumulated vegetation. In many cases, some congestion around an orifice or weir can be tolerated. However, the hydraulic characteristics of the structure are modified by the accumulated matter which prevents the precise quantitative control of discharges towards which irrigation managers strive.

Heavy accumulations of debris at gates and intakes can cause impairment to these structures. Further damage to irrigation and drainage infrastructure may be generated by the growth of weeds, particularly emergent weeds with their extensive rhizome systems. Death and decay of the rhizomes leaves small tunnels through which water seepage may occur, leading to breaches in the channel banks. Similar tunnels are also created by rodents and crustaceans which feed on and amongst the vegetation (Brezy and Mehta 1970). In these ways weed growth reduces the conveyance efficiency of channels and increases the risk of breakdown of supply.

3.7.5 Disease

Dense growths of aquatic weeds create or alter habitats which can then favour the development of disease vectors. Two of the most important vectors which depend on the environmental conditions prevailing in aquatic vegetation for at least part of their life-cycle are aquatic snails and mosquitoes. These organisms are responsible for the transmission of several diseases which affect mankind (Biswas 1980) (Table 3.4).

Table 3.4. Selected examples of vector-borne diseases associated with aquatic habitats

Parasites	Diseases transmitted	Vector	Infection route
Nematoda			
Wuchereria bancrofti	Elephantiasis (filariasis)	Mosquitoes (*Aedes* sp., *Culex* sp., *Anopheles* sp.)	Bite
Protozoa			
Plasmodium sp.	Malaria	*Anopheles* mosquito	Bite
Trematoda			
Schistosoma haematobium	Urinary schistosomiasis (bilharziasis)	Aquatic snail (*Bulinus* sp.)	Through the skin
Schistosoma mansoni	Intestinal schistosomiasis	Aquatic snails (*Biomphalaria* sp., *Australorbis* sp.)	Through the skin
Schistosoma japonicum	Visceral schistosomiasis	Amphibious snail (*Oncomelania* sp.)	Through the skin
Viruses			
Over 30 mosquito-borne viruses are associated with human infections	Encephalitis; dengue	Mosquitoes (including *Culex* sp., *Aedes* sp.)	Bite

The diseases listed in Table 3.4 are not new. However, the unprecedented expansion of water resource developments, including irrigation, has introduced these diseases into previously uncontaminated areas Oomen *et al.* 1988; 1990). For example, an association between the extension of irrigation and an increase in schistosomiasis (or bilharzia) has been widely demonstrated (Biswas 1980). Schistosomiasis is now endemic in over 70 countries world-wide, and affects over 200 million people (Doumenge *et al.* 1987). Water resource developments such as irrigation extend the available habitat for aquatic weeds and the snail vectors of schistosomiasis and thus increase the opportunity for human contact with the disease parasites. The density and reproduction of snail populations are strongly associated with aquatic weeds (Dawood *et al.* 1965; Dazo *et sl.* 1966; van Schayck 1985; 1986; Madsen *et al.* 1988). In canal irrigation systems, the most important sites for the transmission of schistosomiasis are usually earthen tertiary or quaternary canals where there is often abundant vegetation, snail densities are high and human contact with water is greatest (Madsen *et al.* 1988).

The costs of attempts to control the diseases listed in Table 3.4 are high and impose a burden on the economies of many tropical and sub-tropical countries (Coates and Redding-Coates 1981). Furthermore, the magnitude of the effect on populations in terms of the reduction in workforce, loss of work hours and so on can hardly be estimated, not to mention the more compassionate considerations of these debilitating diseases.

3.7.6 Competition with crops

Heavy weed infestation is one of the principal causes of low grain yield in rice (de Datta and Bernasor 1973). Weeds adversely affect germination, interfere with the establishment of seedlings, and later compete with the crop for nutrients, thereby reducing crop yields (Madrid *et al.* 1972; Soemartano 1979; Assemat *et al.* 1981; Majid and Akhtar Jahan 1984). In the context of these guidelines it is important to recognise the potential for irrigation and drainage systems to provide a source of crop weeds and a means for propagules (reproductive parts) to be transported from the channels to the fields, especially in the case of crops such as rice.

3.8 Recording the condition of irrigation and drainage channels

This chapter has shown the importance of weed communities and the successional cycle. Effective weed management requires a system for describing the weed-related condition of a channel as it varies with time.

The condition of a canal or drain at a particular time depends on the degree of structural and dimensional deterioration, and the degree of weed infestation and siltation. The condition worsens over time, but it may be improved by maintenance operations. Common engineering practice is to use relative grades to describe the condition of a channel e.g. good/fair/poor/bad. This works well in annual surveys of the need for maintenance. It is a subjective system however which would be difficult to use at different times of the year when irrigation requirements are low and a poorer channel condition can be tolerated.

We suggest the use of the simple descriptions of the weed communities supplemented by a note on the presence/absence of specific problem weed species. Our experience with operations and maintenance staff in Zimbabwe and Kenya has satisfied us that they could use this system satisfactorily to monitor and record the actual condition of each channel on a regular basis (e.g. monthly).

Weed clearance improves the hydraulic performance of a channel, recovering the weed-related condition from a 'poorer' to a 'better' state by returning it from a later to an earlier successional stage. The extent of the recovery is dependent on the degree of weed clearance. Dredging (or de-silting) operations, for instance, remove weeds and their root material as well as silt, thereby returning the channel to an earlier stage of succession than other weed clearance operations.

Following weed clearance, the successional process recommences. The rate at which it proceeds depends on the channel type, the persistence of the remaining vegetation and the potential for invasion and colonisation by new weeds as well as the frequency of weed clearance operations.

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Plate 3.1 Examples of the four aquatici weed types: (a) submerged (*Potamogeton sp.*), floating-leaved (rooted to the channel bottom) (*Aponogeton sp.*), (c) free-floating (*Azolla sp.*), and (d) broad-leaved emergent weeds (*Polygonum sp.*).

Plate 3.2 Cycle of aquatic weed growth in an irrigation channel following maintenance (see Figure 3.3)

Plate 3.2 Cycle of aquatic weed growth in an irrigation channel following maintenance (see Figure 3.3)

CHAPTER 4

GUIDELINES ON IDENTIFICATION OF FEASIBLE CONTROL METHODS

4.1 Introduction

Textbooks on aquatic weed control typically illustrate the wide range of techniques which are available for the management of aquatic weeds in channels systems (e.g. Pieterse & Murphy 1990; Riemer 1984). These focus on mechanical and chemical methods with some consideration of manual and biological techniques. In reality, the methods which are used for a particular scheme tend to be based on tradition, i.e. what has been used in the past, and on opportunity, e.g. the availability of a particular type of machine and the funding to purchase or hire it.

In many irrigation schemes in developing countries manual control is the traditional means of control and hence forms an important component if not the most important in maintaining the system. Information on the different manual techniques is therefore essential and this chapter includes a focus on this set of techniques. This information can be used as a basis for either a change to a different form or forms of manual control, or an adaptation of existing tools, e.g. providing longer handles or including the use of a secondary tool such as a rake.

Where the opportunity arises either to acquire a machine or to bid for funding, it is necessary to consider the advantages and disadvantages of the various types of mechanical devices which are available. The main different types of machines which could be used in irrigation and drainage channels are described and information provided on the advantages and disadvantages associated with them.

Consideration is given to the use of herbicides, environmental techniques and the potential of biological control agents.

An aquatic plant management strategy should be flexible and able to deal with different types of weeds in the various different types of channels. In a particular situation, the combination of one or two methods may be appropriate. for example, a strategy might be based on:

a. Use of an hydraulic excavator with a weed cutting bucket with a reach sufficient to deal with the majority of the arterial channels and with the potential for dealing with one-off situations in other parts of the system.

b. Regular use of manual clearance of weeds based on a range of tools. These tools would be used for specific tasks, e.g. chain scythe for submerged vegetation removal in large channels and rakes for removal of submerged vegetation in smaller channels. These tools should be such that there is no need for the operative to enter the water.

c. Occasional control using a herbicide. A herbicide should only be used to deal with one-off problems which could be site or species related. Precautions would need to be taken to ensure that only the weeds were damaged. Such usage should include a full programme for that site or species to ensure lasting control, i.e. a single application is unlikely to be effective.

d. Planting trees along carefully chosen channels can effectively limit aquatic plant growth through shading and act as a cost efficient means of weed control. Such trees can also provide a timber crop if only for fuel when selectively cropped.

e. Identification of the different types of weed species with a consensus being reached on which weeds need the most effort putting in to control them. Attention needs to be drawn to other species which although not known from a given irrigation system, might colonise it and need immediate attention.

f. Aquatic plant management should be seen as:

- a joint responsibility between authority and farming community
- an on-going maintenance requirement
- different from weed control in the field or crop situation in that aquatic vegetation is important in the channel for stabilising banks, sheltering and providing food for fish and providing forage for livestock.

Figure 4.1 provides a series of flow charts to aid the selection of appropriate aquatic weed control measures.

4.2 Manual control

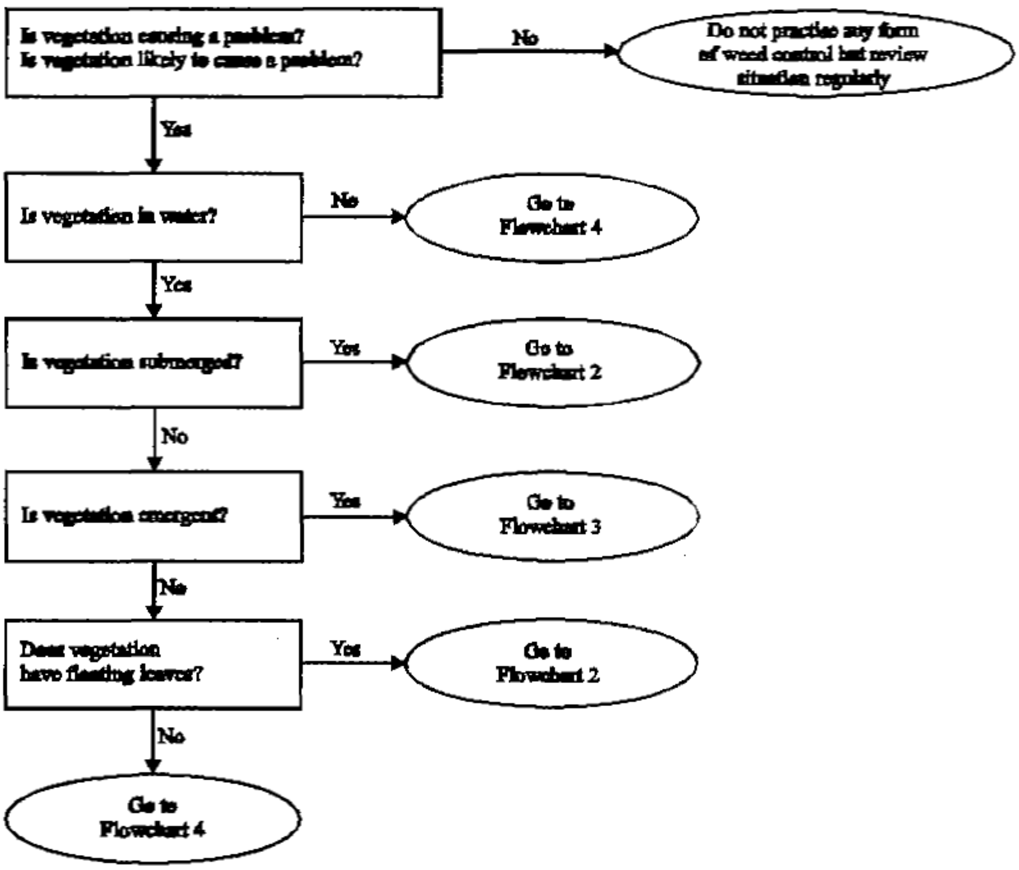
4.2.1 Introduction

Manual techniques include pulling, raking and cutting and until recently these were the only means of weed control. Today they remain important in many parts of the world and especially in those countries where labour is readily available and cheap. However, success is variable due to such factors as the extent of weed removed. For

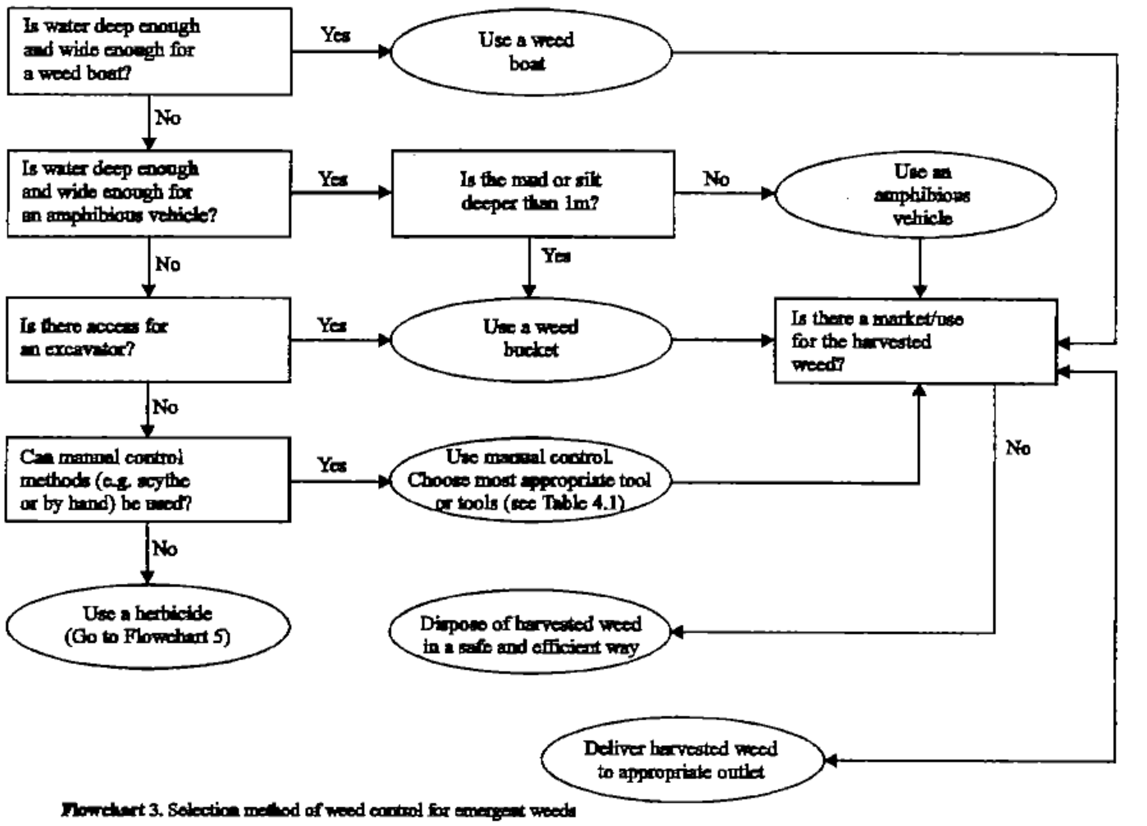
Figure 4.1. Flowcharts to aid the selection of the most appropriate method of aquatic weed control

Flowchart 6 presents the decision route where herbicides are the preferred option

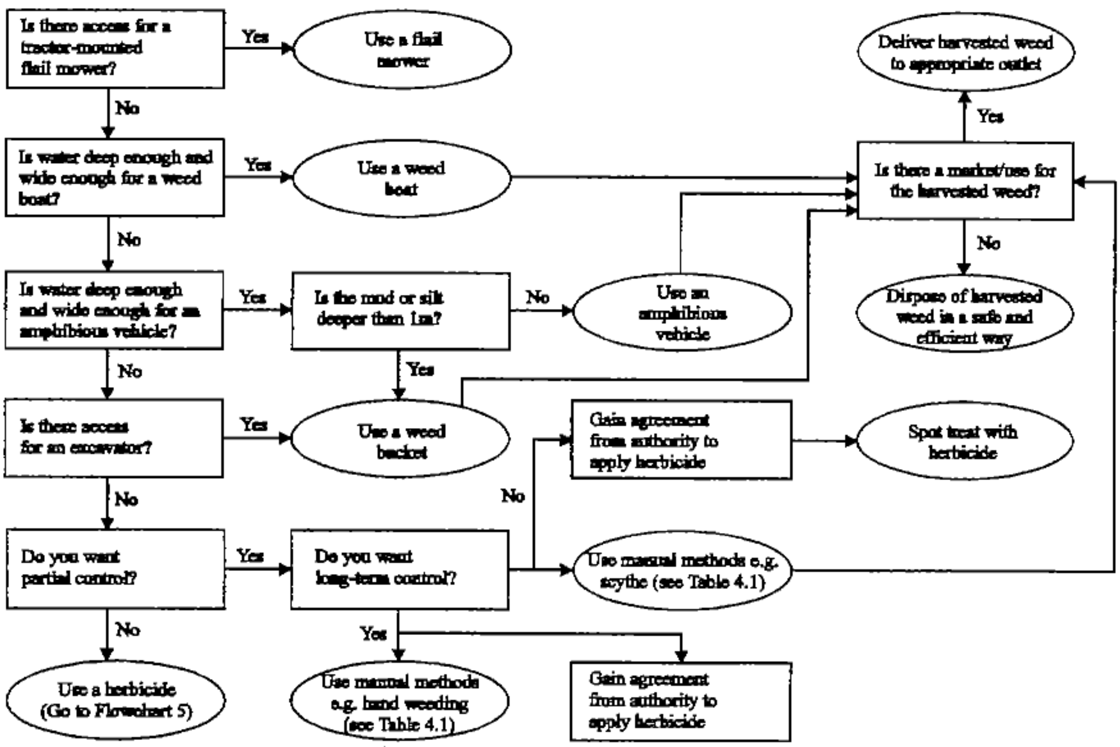
Flowchart 1. Selection of appropriate method



Flowchart 2. Selection method of weed control for submerged and floating weeds

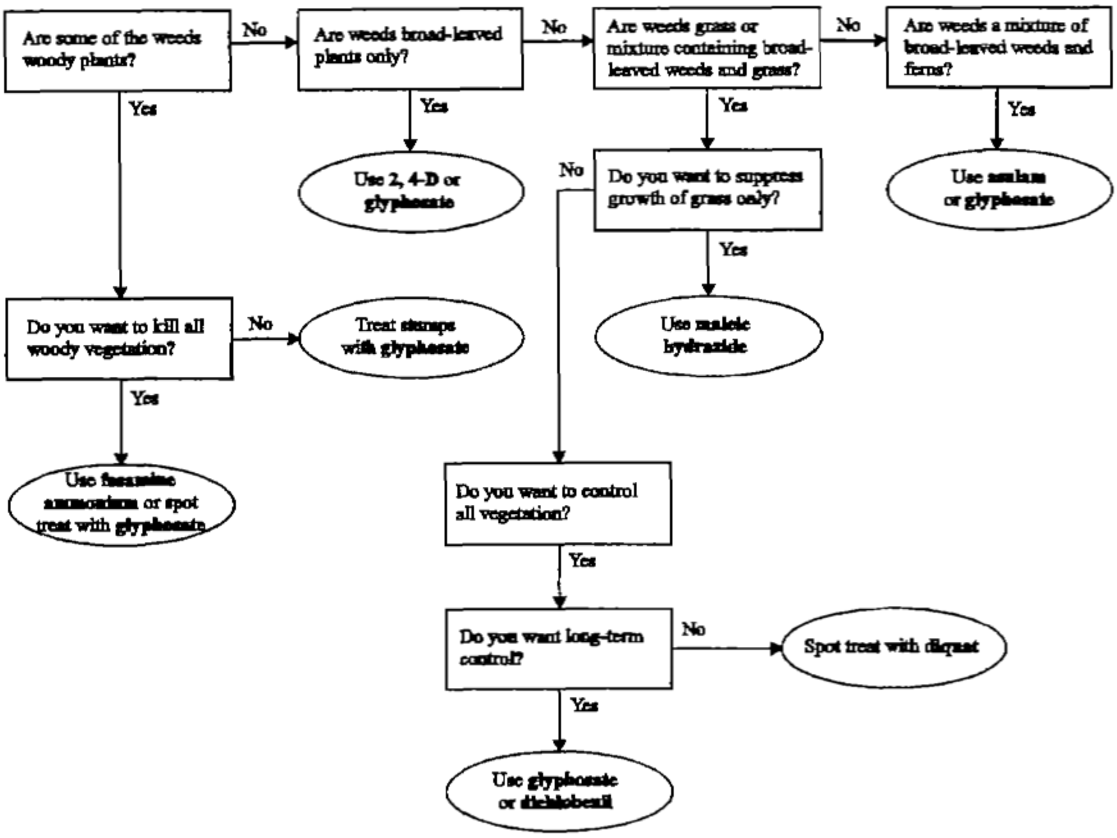


Flowchart 3. Selection method of weed control for emergent weeds

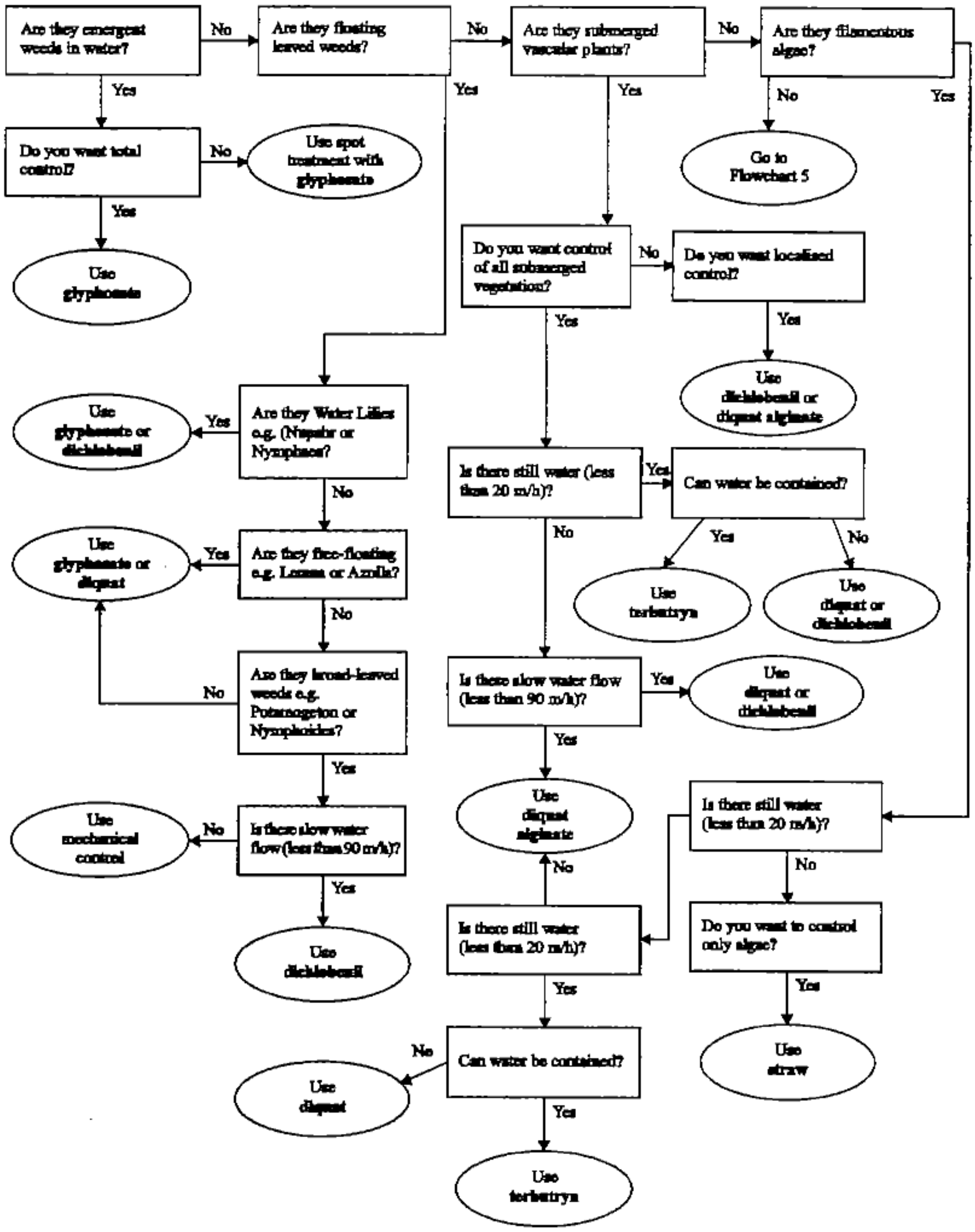


Flowchart 4. Selection of method of weed control for bankside weeds

NB. Always ensure that permission/license has been granted for use of a herbicide. Always follow the instructions on the manufacturers label.



Flowchart 5. Selection of most appropriate herbicide for aquatic weeds. NB Always ensure that permission/licence has been granted for use of a herbicide. Always follow the instructions on the manufacturer's label



example, in India 50% of manual treatments of the free-floating *Eichhornia crassipes* achieved only partial success, with 25% total success and 25% failure in the remainder of the treatments (Varshney and Singh 1976). In programmes for *Salvinia* clearance it was essential to have follow-up treatment in order to achieve lasting control, up to three manual cuts being reported for some channels. Without this, complete reinfestation can occur. Examples of successful or partially successful (65 to 90%) treatments have been reported for *Nelumbo nucifera*, *Pistia stratiotes*, *Nymphaea stellata*, and *Hydrilla verticillata* (Wade, 1990).

The hand-held implements currently in use for controlling weeds in irrigation and drainage systems are mostly modified forms of traditional tools used for agricultural purposes. In most cases they have been developed by the operators themselves to meet a local need. As a result, a range of tools, differing widely in their shape and performance has evolved and has until recently been handed down from generation to generation with little alteration.

Plate 4.1 illustrates some of the manual techniques which can be used in irrigation and drainage channels. Table 6.1 provides a summary of the productivity of labour which has been achieved using different hand tools for aquatic weed control in channels.

4.2.2 Manual tools

There is a wide range of hand-held tools for cutting and clearing aquatic and bankside weeds (Plate 2.1). The long-handled nature of these tools is not only to provide a good reach into the wider channel, but to prevent the worker from having to enter the water. These tools include:

4.2.2.1 Chain knives and chain scythe

The chain scythe is made up of 5-10 scythe blades, depending upon the width of the watercourse, each 50 cm long. The blades are bolted together loosely so that they can make hinge-like movements. The bolts are secured by split pins. Each of the two outer blades has an eye for fastening a rope. Variations on this these are simple a heavy chain or cable or an A-frame.

The construction of the chain scythe allows it to operate close and parallel to the bottom of the watercourse cutting through and uprooting submerged and floating species of plants. The gang operating the chain scythe consists of three labourers: two handle the scythe, one on each bank of the watercourse, while the third person collects the cut plant material accumulating at a barrier, culvert or other obstruction. The scythe operators lower the tool obliquely across the watercourse into the water at the downstream end of the reach so that the cutting edges of the blades point in the direction they are going to work. They operate the tool by pulling at the ropes in turn while walking slowly forwards, so zig-zagging the chain scythe over the bottom. This tool is very effective against such plants as *Potamogeton* species and young shoots of *Phragmites* and *Typha* (Druijff, 1979).

It is not possible to operate this tool using manpower under all conditions, and the following should be complied with:

- the cross-section of the watercourse must be more or less curved without sharp angles so that the chain scythe can touch the bed at all points
- the banks must be clear of trees, posts, barbed wire and other obstructions
- abundant weed growth along the banks must be removed before using this tool
- stones, pieces of metal and other such items should be removed from the channel in order to avoid premature blunting of the edges of the scythe
- the maximum surface width of a channel which can be cut using a chain scythe is about 6m.
- the water depth should be no less than 50 cm so that there is enough water to brace the weeds when they are being cut.

Some 500 m per hour actual working time can be cleared with this tool. Assuming a working day of eight hours, two of which are spent on sharpening and maintenance and another two on rest and moving from one location to the next, the daily production figure will be some 2,000 m of watercourse for three labourers (Druiff 1979).

Where there is substantial weed growth, in addition to the two workers pulling the chain scythe, four to five more will be needed to follow on, pulling out the cut weeds onto the banks using long-handled forks.

4.2.2.2 Scythe

With a sharp horizontal 0.6 to 1.0 m long blade and its long wooden handle set at roughly right angles to the blade, the scythe is perhaps one of the most successful hand-held tools. Its handle has been modified a little but it is virtually the same tool as used in Europe for centuries to cut hay. Some skill is required to operate it, but once its use has been mastered, it is a very efficient means of cutting submerged weeds and can also be used for the grass, sedges and reeds on the bank. In skilled hands it gives a closer cut than with mechanical cutters and results in slower regrowth. It also enables the operative to be selective in the weeds removed.

4.2.2.3 Clearing scythe

This tool consists of a sturdy blade on a curved steel handle with adjustable grips. A short curved knife is attached to the back of the handle near the blade to enable heavy woody stems to be cut. The tool is operated with short jerks unlike an ordinary scythe which is operated in a long flowing movement. It is ideal for cutting weeds growing along the banks of a watercourse close to the water's edge such as species of *Typha*, *Phragmites* and *Cyperus*. A skilled worker can use the tool so that most of the cut weed is deposited on the banks.

This tool is too light to be used in neglected watercourses with heavy weed infestation. Some skill is required to use the tool correctly and to avoid injuries to the legs.

The productivity in a well kept watercourse amounts to 150 m per effective working hour. Assuming a working day of eight hours of which two are spent in sharpening and maintenance and another two on rest and on moving from one location to the next, the daily production will be some 600 m on one side of a watercourse per person day (Druiff 1979).

4.2.2.4 Sickle, reed sickle and grass hook

Sickles and grass hooks with curved blades, and other tools used for cutting grass and weeds on dry land are also used in the water (Plate 2.1). Usually they are attached to longer handles so that the weeds on the bottom can be reached more easily. The labourer puts the sickle behind the stems, just above the roots. The weeds are severed from their roots by short jerky pulls.

4.2.2.5 Ditch bank knife or ditch bank spit knife

As its name suggests, the ditch bank knife consists of a sturdy knife, approximately 50 cm in length fixed on a long wooden handle 3 m in length. Around the shaft of the knife at the point where it is fixed to the wooden handle, a 2 m length of rope is fixed. The tool is operated by two individuals: one holds the handle and moves it up and down in such a way that the knife cuts the stems of the weeds while the second pulls the knife forward with the rope. It is particularly effective against non-woody weeds and in particular creeping plants such as *Ipomoea* species, which can begin raft formation. It can also be used to cut submerged weed. Due to its trailing nature and attached soil, the cut material does not easily flow downstream and a third person is needed to remove the plants with a digging fork.

The blade does not have to be as sharp as a scythe blade and if it is hammered out too thinly during maintenance, it will soon bend under the force exerted on it when passing through the ground.

4.2.2.6 Digging fork

The digging fork, most suited to cleaning operations along watercourses, has four to five heavy tines more or less at right angles to the handle. It is used to remove weeds cut loose by the ditch bank knife, and it can also be used in landing heavy floating aquatic weeds such as *Eichhornia crassipes*.

4.2.2.7 Slasher

A slasher is typically a long sword-like blade sometimes with a hand-grip at the end (Plate 4.1). The cutting end (15 cm) is bent at an angle to the main length of blade. The tool is swung to and fro to slash the vegetation just above ground level. It is particularly useful for cutting down bankside and marginal emergent vegetation. Cut vegetation should be removed from the channel and channel banks as it may propagate reducing the efficiency of the technique. A slasher can be used to good effect in a channel which has been dried out.

4.2.2.8 Rake and fork

Rakes and forks have been produced in which the handles and tines are longer than normal, and the tines are bent over. Such a type of fork is sometimes known as a crome. They are useful for removing cut plant material and filamentous algae. They are also used from the bank to drag out submerged plants without cutting but a proportion of stems always remain behind and although they may be damaged regrowth is usually rapid. Likewise, raking is unlikely to remove every bit of the plant materials, e.g. free-floating species, and regrowth will necessitate the procedure to be repeated. Forks have been used to lift floating plants of *Eichhornia crassipes* into barges but this is a slow operation and applicable only to small infestations or mopping up after using another form of weed control, e.g. mechanical cutting.

4.2.2.9 Hoe or long handled digging hoe

This tool looks similar to the traditional garden hoe but holes should be made to reduce resistance as it is pulled through the water. The hoe is fitted with an aluminium or wooden shaft 4 m in length. Shallow hoeing along the banks and beds of channels can be used to remove all the above ground material and some of the root or rhizome system (Plate 2.1). It is a selective technique which can be aimed at specific species and can be used in irrigation channels which have been dried out. If not undertaken with care, hoeing can draw earth from the banks into the centre of the channel thereby altering the channel profile. When hauling spoil onto the side of the channel, the handle is supported on the shoulder to enable more effort to be put into pulling the tool. The cutting edge of the hoe should be sharpened with a file. The connection between the socket and shaft should be checked. When there is some play in this, a wedge should be driven down the shaft near the socket.

4.2.2.10 Booms and barriers

Whilst a long-handled rake can be used effectively for clearing free-floating plants in narrow channels, for wide channels a barrier or floating boom may be preferable. This can be made from materials such as bamboo, a rope threaded through cork floats, a chain of barrels, or inflatable rubber units. The barrier needs to permit water to pass through it and to be able to conform to wave and wind action.

4.2.2.11 Netting

Small floating weeds, such as *Lemna* and *Azolla* species, can be skimmed from the surface of channels using drag-nets. The nets for manual operation, for example, from a hand rowed boat, are usually made of 3 mesh coir ropes.

4.2.3 Manual control in irrigation and drainage channels

There are essentially two approaches to manual weed control contracts:

a. periodic contracts in which third parties carry out weed control in a definite time period, e.g. one month;

b. lengthman contracts in which third parties are made responsible for the state of maintenance of a certain stretch throughout the period of one year (i.e. one complete growing season).

In both cases the cost or rates paid to the workers depend on such factors as top width of the channel, degree of weed infestation and length of channel to be managed. In a study of the Fayoum Water Management Project, Egypt, for an average sized canal with normal weed infestation, a daily productivity of 30 m per labourer, measured on both sides of the channel can be obtained. It was estimated that two periods of maintenance are necessary per year to guarantee a proper waterflow in the canal. Shortages in labour availability can be encountered in certain situations. These are usually related to the likelihood of contracting schistosomiasis or to higher wages being offered for work in the fields (Euroconsult 1994).

Manual weed control is widely practiced in the maintenance of irrigation and drainage channels. It has a number of advantages:

- very little foreign currency is needed to purchase the tools
- the tools do not require complex maintenance
- very little training of labourers is required
- a cheap form of control where labour is abundant
- operations can be easily contracted out once the management has gained some experience
- little need to upgrade inspection paths
- very selective and allows maximum control over the amount and type of weed removed
- usually produces predictable results when combined with follow-up treatment
- provides opportunity for utilisation of vegetation

The main disadvantage is that manual control can bring the operator into contact with water which is likely to be infested with schistosomiasis.

In order to maximise on this efficiency there are various questions which need to be asked:

- What is the basis for current manual control?
- Which type of vegetation does it deal with?
- Is it aimed at cutting or does it include removal?
- Is cut material put to any use? If not, why not?
- Could other tools be used to deal either with other types of weed (e.g. a rake to remove submerged vegetation) or more efficiently with weeds currently managed (e.g. a long handled scythe as opposed to a short handled scythe)?
- Are there health hazards and how can these be minimised?
- Are there labour supply constraints?

In order to answer these questions it is important to examine the range of tools currently used and consider their advantages and disadvantages. Table 4.1.

Table 4.1 Appropriate manual control methods for aquatic plants

Name of plant	Main method of spread	Recommended method	Alternative method
1. Free-floating & submerged unrooted			
Salvinia, Lemna, Eichhornia, and *Ceratophyllum*	Budding	Raking (short term only) Netting	Herbicide or mechanical
Filamentous algae	Cell division	Raking (short term only)	Use of straw[1]
2. Submerged, rooted			
Egeria, Hydrilla & Potamogeton	Roots, stem fragments & occasionally seeds	Cutting and hoeing with harvesting using booms/barriers	Raking, herbicide or mechanical
3. Floating leaved (rooted on bottom)			
Nymphaea & Nymphoides	Rhizomes & rhizome fragments	Scything, cutting (e.g. scything) below water level	Mechanical cutting or herbicide

4.2.4 Selecting the best tools

Manual control can be broadly divided into digging out or cutting. Digging out plants complete with their roots or rhizomes is a very effective method for controlling emergent species at the water's edge. Cutting is much quicker than digging, but less effective, because the roots remain and it will need to be repeated more often. Cutting the emergent plants at the base of the stems can be done using hand tools or, in deeper water, using a chain scythe. Where possible emergent plants should be cut below the water surface to maximise damage. alternatively the channel could be flooded after cutting in order to achieve the same effect.

Raking can provide useful control of most free-floating and surface plants such as *Salvinia* and filamentous algae using a long-handled rake or boom.

When choosing tools for manual control and devising a maintenance strategy it is important to consider the following:

- The work force should not have to enter the water in order to carry out their tasks. If this is the case the wrong tools are being used. There is often a risk of schistosomiasis in irrigation systems as well as other water borne diseases.
- The bankside habitat can harbour animals such as snakes and the cutting pattern should be such that this problem is minimised.
- The work force should respect the water in the channels and not foul them. It might be used for drinking and washing purposes.

[1]for explanation of this method, see section 4.5

Each different method has its own advantages and disadvantages and these need to be considered in relation to the irrigation and, or drainage channels under consideration. Modifications to a particular tool might be appropriate to make it better fitted to dealing with a particular species or channel type.

4.2.5 The importance of channel type

Manual clearance will vary from one channel type to another. These can be divided into four main types:

a. Main channels with a significant flow. The principle advantage in this type of channel is that having cut the weed it can be carried downstream by the flow and collected by raking at an appropriate point either using a boom or a fixed control structure. The latter are typically serviced by a track or road where material needs to be transported away.

   Larger channels pose problems due to width and depth. A useful tool to consider is the chain scythe which is operated from both sides of the channel and is particularly suitable for submerged and rooted floating vegetation. Given that main channels should not support significant emergent growth, such a tool could deal with most of this type of channel.

   When dealing with free-floating vegetation it is important to be thorough in removing the plant material. Typically they reproduce from an individual plant, the population doubling each time it reproduces. The removal programme should be started upstream working down the channel to minimise reinfection.

   The task of dealing with submerged and floating weeds can be reduced by mowing the vegetation on the banks to facilitate access prior to maintenance.

b. Medium sized channels can support the full range of plant growth and whilst a chain scythe might be appropriate in certain channels especially where there is significant flow, in others long handled tools are likely to be more efficient. Submerged and floating vegetation are the more usual types of weed and it is recommended that effort is made to keep these weeds under control. If they are left to develop mats growing out from the margins or as islands in the middle of the channel, they will be colonised by emergent species and the problem of maintenance will increase dramatically.

   Where emergent vegetation has achieved problem levels, a team approach is necessary to rake out, or cut and rake out the leaf and root or rhizome material. The latter are often extensive and difficult to break up.

   As with main channels thorough removal of free-floating vegetation is essential. Mowing the vegetation on the banks to facilitate access prior to maintenance, can be very helpful.

c. A range of hand held tools is available for smaller channels which are in water perennially (see 4.2.2 Manual tools) and it is likely that more than one tool will be needed to satisfactorily deal with the range of vegetation encountered.

   A technique for dealing with emergent vegetation is to drop the water level in the channel and to cut the plants low enough so that when the water is allowed to return to its normal level the cut stems are below the surface. This is known to severely inhibit if not prevent regrowth in some species, e.g. *Typha* species. The same might be true for other species.

   The smaller channels are typically the responsibility of the farmers. Working together on each others channels can be more efficient and safer.

d. In the smaller channels which occasionally dry out, aquatic plants are rapidly damaged when the water is drained out of a channel. In order to maximise the damage make sure that sluices and other such structures do not leak. On the other hand be careful that drying out does not cause the bank to crack and lose water on refilling.

In addition to the options available in (c), it can be advantageous to wait until the channel is dry and to remove the vegetation at this stage, e.g. using a hoe. The channel is easier to work in and because of the absence of water the vegetation can be lighter to work with. Submerged and floating species will rapidly dry and decompose but remember that for many submerged species and for rooted floating species, the root and rhizome systems remain viable. If these plants have become a serious problem, clearance when in water might be preferable in that the roots and rhizomes can be more easily removed.

Channels which can be allowed to dry out also offer the potential for burning the unwanted vegetation and hence removing the bulk of the material. This is particularly valuable for emergent vegetation and can also reduce the viability of propagules. Piling up the material and burning in a light to moderate wind is the most effective means of burning, generating sufficient heat to kill the seeds of most species. Remember however that the ash which remains will act as a fertiliser for the plant growth once the channel has been refilled and a bloom of algae or submerged vegetation is typical. When using fire it is necessary to take precautions to limit damage to the treatment area. Comply with local laws and guidelines and use breaks of sufficient width to stop uncontrolled spread.

Burning is not necessarily a good idea and depends very much on the species being managed. Some, for example, *Phragmites australis*, will grow more densely and vigorously after burning than before due to the breaking of dormancy in buds or an increase in the amount of available light due to removal of accumulated leaf litter.

Do not rely on burning in case the weather prevents the vegetation drying out sufficiently for it to burn thoroughly.

4.2.6 Maintenance and training

Once a maintenance strategy has been established including decisions on which tools to use, a check needs to be undertaken to ensure that:

- the workforce is trained in the efficient and safe use of any new tools;
- the necessary equipment is available in order to maintain the tools, e.g. new blades and sharpening equipment;
- replacement tools are available in case of irreparable damage to or loss of those in current use.

Maximum advantage of manual control is only achieved when the workforce is familiar with the different types of vegetation in the channel. This could range from knowledge of species which are notoriously difficult to cut or rake, to those which are advantageous, e.g. important for bank stabilisation or useful as a food source. Such knowledge can be gained gradually or taught in a more structured manner. Where it is learned gradually, it is necessary to make sure that the knowledge is passed through the whole workforce and also on to new staff as they arrive. Check that everyone is using the same names for the various species which have been identified and record this information including observations on distribution and the seriousness of the species as a weed. This helps to identify problems as they develop, rather than having to wait until they are becoming insurmountable.

If a workforce is to be taught in a more structured manner make sure that there is the necessary support, e.g. an identification aid/manual and an explanation as to why a knowledge of the weeds can be so valuable. An effective aid is a collection of plants either as fresh material collected immediately before the training session, or as dried specimens put on to card and kept as a reference collection. The latter can be labeled up and, if the opportunity arises, shown to a botanist to check. Such dried specimens on card can be photocopied and made up into a field guide. Again, check that everyone is using the same names for the various species which have been identified and record this information including observations on distribution and the seriousness of the species.

4.2.7 Appraising performance

Success with a revised maintenance programme will not be immediate especially where a new tool or tools are involved. The workforce will need time to adjust to new techniques and to learn about the different weed species. Nevertheless it is necessary to appraise the success of the programme against the hydraulic objectives established.

It might be necessary to try out different ways of working with a new tool though this is best undertaken in the training period prior to implementing the programme.

4.2.8 Poisonous plants

Livestock usually avoid poisonous plants because they tend to be unpalatable. Cutting, and also dredging and herbicide treatments, can increase the danger to livestock in three ways:

a. the plants and particularly the roots can be exposed and moved up the bank so that they are more accessible to animals;

b. the cut vegetation may be mixed with palatable species so that poisonous material is eaten accidentally;

c. several of the more poisonous species become more palatable after being cut or sprayed but can remain poisonous as long as dead plant material remains intact.

Use local knowledge to identify if poisonous plants are present in or along the banks of channels and take precautions where necessary to fence off or remove the cut or treated material containing the poisonous plants.

4.3 Mechanical control

The diversity of machines devised to cut, shred, crush, suck or roll aquatic weeds is wide. This assemblage of machines can be usefully divided into two groups:

1) those aimed at cutting and/or otherwise removing solely the aquatic weeds;

2) machines which have other functions apart from weed cutting and/or removal, for example, dredgers.

Some of these machines are water-based on boats and barges, others work from the bank and shore, mounted on tractors or as purpose built machinery. Useful reviews of machines are provided by Gopal (1987) and Wade (1990).

Flowcharts 2 and 3 (Figure 4.1) assist in making a choice of appropriate mechanical methods.

4.3.1 Cutting, chopping, shredding and harvesting

4.3.1.1 Floating machines

Floating machines are used mainly to manage floating and submerged weeds and early devices were simply rakes or other pieces of farm machinery, weighted to keep them from riding up over the weed beds whilst dragged behind boats. The scratching and scraping action dislodged and broke off the weeds. Smaller weed-cutting boats were developed in Europe and North America which used a V-shaped knife with either a serrated or a straight edge pulled along the channel bottom behind the boat. The blades dulled easily and required an even bed devoid of solid obstacles, such as tree branches and rocks. The design of these weed cutting boats soon advanced to make use of reciprocating cutter (or mower) bars, initially horizontal straight bars1 to 2 m long, lowered and fixed to cut at a required depth. In some devices the bar could also work at an angle to and above the water surface cutting emergent vegetation along lower parts of the bank. U-, K-, and inverted T-shaped cutter bars were the next step forward in design, coupled with hydraulic control of the depth and angle of the cutter bar in the water.

The 1 to 2 m swath cutter bars of the smaller boats were increased to 3 to 5 m to fit onto barges, improving their capacity for cutting weed. A wide variety of models based on this design has been marketed. The basic design is a flat, self-propelled barge with a steel hull capable of working in very shallow water. Propulsion is typically by paddle wheels, which increase manoeuvrability and give a shallower draft. Two hydraulically-controlled arms extend from the front of the boat and a U-shaped reciprocating cutter bar is fastened between them.

The problems of propulsion of weed cutting boats have led to the exploration of alternative methods designed to overcome the problems of fouling by weeds. Different designs are needed for different types of water: independent hydraulically-driven paddles are ideal for small craft in larger drainage and irrigation channels with steel propellers being more appropriate in fast-flowing channels. The type of hull also depends upon the situation in which the boat is to be used. Steel is usually the preferred material, though moulded fibreglass is better for boats which have to be moved from one channel to another.

The early cutting, crushing, and shredding devices, both small and large, had a major drawback in that the treated plants remained in the water. Decomposition of the shredded material and a certain proportion of cut material caused undesirable effects by depressing concentrations of dissolved oxygen and producing unsightly heaps and obnoxious smells along the margins of water bodies. The breakdown of the organic material in the water also released inorganic nutrients which resulted in algal blooms and the increased growth of aquatic weeds. Cuttings of submerged plants could float in the water almost indefinitely and fragments of many species have the ability to root and regrow. The free-floating nature of the material meant that plants were able to move around or along a water body with the potential for new infestations. The fragment of plant from which regrowth can occur may be very small. In *Panicum repens* , for example, a one-node cutting 5 cm long is all that is necessary (Siregar and Soemarwoto 1976). Problems also arise from cut plants blocking screens, spillways, and channels.

Two solutions were explored to overcome these drawbacks: improving the effectiveness of the shredding and chopping, and harvesting the weeds. The former approach does not overcome the problems of deoxygenation and nutrient release. Harvesting, or removing the weed from the water body, has become an essential part of physical control. However, such harvesting is often time consuming and is usually the limiting factor in such mechanical control.

Techniques for harvesting the mass of cut weed range from manual raking using wind and current to concentrate the weed, through the application of dragline cranes, to sophisticated machinery with dewatering and baling facilities. Machines can also be fitted with fragment barriers. A typical system in an irrigation channel network involves one or more porous conveyor belts which pick up the weed from the water and transfer it to the bank of the channel, preferably at points where the cut and harvested material can be transported away. Further transportation of the cut weed is frequently necessary, to a site where the nuisance weed may be utilised and/or allowed to decompose. Smaller weed cutting boats now have the facility of changing the cutter bar for a rake (4 m in width), which collects the weeds together and using the hydraulic arms lifts and dumps loads of up to 300 kg of weed onto the bank. The nature of the bucket or rake depends on the species being harvested, for example, free-floating non-rooted plants require a fine mesh bucket.

The large quantities of unwanted water associated with harvested weeds are a major problem and presses can be used to reduce the weight of the load by 68 per cent and the volume by 16 per cent, although some organic matter is lost to the water (Bagnall 1980a,b).

The enormity of the task of weed control in heavily infested waters gives an immediate indication of the limitation of this method of weed control. Given a standing fresh weight crop of vegetation of 376 tonnes ha^{-1} and a modern weed harvesting operation which can remove approximately 1 ha of weed per hour, a crew attempting to control such an infestation from a water surface area of 160 ha would still be working four-five weeks later (Ramey 1982). The limitations are equally apparent with species capable of rapid regrowth. Culpepper and Decell (1978) calculated that harvesting systems with a disposal rate of 80 to 100 tonnes per hour were necessary for such species as the free-floating *Eichhornia crassipes* and the submerged *Hydrilla verticillata*. Although some come close, few harvesters appear able to achieve such a performance consistently.

Even if one assumes an efficient operation, there are a number of drawbacks which need to be appreciated in the use of floating machinery, particularly in the management of large water bodies.

1. Much of the machinery in use today has been developed with specific, often local, needs in mind which has produced a proliferation of different types of machines. Careful thought should be given as to the type/model of machine purchased.
2. The economic effectiveness of these machines is hard to estimate due to the complexity of the operation: cutting, harvesting, transportation, and dumping. The period during which the machine is out of action (down-time) also needs to be taken into consideration, as described in Chapters 7 and 8. The hidden advantages of nutrient removal are even more difficult to quantify. Comparisons with other treatments, e.g. herbicides, are therefore difficult.
3. Maintenance of machinery of this type is difficult, particularly for machines manufactured in one country and used in another, and often spare parts are costly.
4. Access to and along a channel may be difficult due to steepness of bank and presence of bridges. Long distances may need to be traveled, not solely to launch a weed cutting boat but also for the transportation of harvested weed away from the site.
5. Shallow waters present severe problems, in terms of the draught of the boat and with respect to the distances which have to be traveled in a large shallow water body.
6. The high cost of such management, exacerbated by the need for repeated treatment and the fact that the harvested weed has little or no value in many countries, may make the operation prohibitive.

On the other hand, there are a number of significant advantages of floating machinery.

1. The degree of selectivity which may be applied. This is of particular importance when vegetation needs to be left for example to benefit and maximise fish production
2. The removal of nutrients from the water
3. A reduction in the long term dependence upon foreign currency as harvesting reduces the need to purchase herbicides
4. Compatibility with terrestrial crops growing near the water body, not necessarily achievable with machines operating from the bank and herbicides

5. The potential for quick and predictable removal of weeds from specified areas
6. The production of useful materials, e.g. green manure and animal feeds.

4.3.1.2 Machines operating from the bank

A range of cutting mechanisms has been developed which operate from the bank of a channel, drain or river (Plate 2.2). Several devices have been developed for use with dragline excavators and the hydraulic attachments available on modern tractors and excavators. The reach of such machinery varies: a tractor-mounted flail mower has a reach of up to 7.24 m; a weed cutting bucket mounted on a hydraulic excavator 11 m and a weed cutting bucket on a dragline 18 m. The machine may be fitted with a weed cutting bucket or a dredging bucket. The most widely used device is the weed cutting bucket, considered to be the most important development in recent years in irrigation and drainage channel maintenance. The bucket is attached to the hydraulic jib of a tractor or excavator and, in operation, the lower edge has a cutter bar which may range from 2 to 4 m in length. The bucket is lowered parallel to the substrate surface and pulled towards the excavator by the jib, cutting the weeds on the way. The bucket is able to cut weeds on the banks and the bed of the watercourse and, given a sufficient reach, both banks can be cut in one sweep. The cut weeds collect in the bucket which does not retain the water and are lifted out and dumped on the bank or in a truck. Depending on the skill of the operator, the bucket can cut above or slightly below the sediment/silt. The main problems with this technique are trees and other similar obstructions which reduce accessibility of the weeds and watercourse from the bank. Additionally, there is a disruption of land use especially where regular maintenance is required. This area of land or the maintenance path is 1.7 to 2 m wide although some machinery is available requiring paths only 1.2 to 1.5 m wide.

The availability of continuous access along the bank top is an important requirement, which may inhibit the use of these methods on many existing channels, for example, channels on the Chisumbanje estate.

A weed rake operated from the dragline excavator is also a popular device, more robust than the weed-cutting bucket.

A range of other equipment has been specifically designed for weed removal from the bank, for the removal of cut weed and especially filamentous algae, and for use on screens at pumping stations. Weed cleared from ditches or canals by weed buckets mounted on a bankside excavator may also be dumped straight onto the bank or onto barges. In flowing waters cut weed is usually allowed to drift downstream, for collection by boom systems.

Rotary, reciprocating and flail cutters provide an important range of machines for cutting emergent and bankside vegetation. A wide variety of small self-propelled pedestrian and ride-on cutters can be used on slopes with gradient less than 2:1 although Allen motor scythes can work across steeper gradients under suitable conditions. Operation of this type of equipment is difficult and tiring and, where access is available, tractor-mounted cutters provide a useful alternative. Such devices are usually operated from a tractor or excavator attached to hydraulic arms. A choice exists between lightweight and heavy duty flails with cutting heads in the region of 1.3 m wide and long reach arms. Adjusting the cutting depth on rotary cutters is difficult and can cause damage to the sward. Damage to the machinery can result from stones and other hard objects such as wire and string which can add considerably to down-time.

The National College of Agricultural Engineering (NCAE), England, undertook a review of existing machinery for the management of drainage channels (Murfitt and Haslam 1981) and indicated that reciprocating drum and disc mowers could be used in any section within the water channel. The rotary devices, although needing higher power, are very much more robust than the reciprocating cutters. Flail cutters/mowers are limited in use to the area above water. The NCAE also defined the design objectives for an ideal machine, which should be robust, reliable, and able to operate in water. It should control rooted and non-rooted weeds at one pass without affecting the stability of the banks. It should have variable geometry to cater for a channel bed of 0.6 to 1.2 m and bank slopes of 30 to 45 degrees and remove the weeds to a stable position above 1.2 m up the bank . Price (1981) presented data on the characteristics of eight weed control machines related to these criteria, giving advantages and disadvantages. Two of the machines which came the nearest to satisfying the criteria, allowing for normal down-time and obstructions (e.g. culverts, side dykes) had an estimated output of approximately 2.4 km d^{-1} and 4.16 km d^{-1}.

Table 6.3 provides a summary of the productivity achieved using mechanical equipment for cutting aquatic weeds in channels.

4.3.2 Dredging

A major disadvantage of cutting and harvesting aquatic weeds, as a means of direct control, is that the underground material is left behind. This is particularly relevant for the submerged and rooted floating plants. More thorough control is achieved by dredging which removes both plant material, including much of the stem and leaf growth, and accumulated sediments. Such operations are usually undertaken from the bank using either dragline or hydraulic excavators (Plate 2.2). Tractor-mounted mud scoops are also produced, usually for use by individual land owners. The draglines have the advantage of a considerable reach whereas the hydraulic excavators may be used more easily to create a steep, uniform batter on the bank or banks, though recent engineering has combined both approaches. Dredging is particularly necessary in cases where sediment and, or organic material has accumulated in the system. and where other control measures would be ineffective.

The effectiveness of dredging depends upon a number of factors and, in particular, the depth of mud dredged from a water body and the depth of water after dredging.

The intervals between dredging are much longer than intervals between weed cutting, for example, and the degree of control is usually sufficient to negate the need for other control, e.g. herbicide application or cutting, for at least one full season. Further advantages accrue in that sediment removal extracts plant nutrients and where the depth of water increases, the amount of light penetrating to the bottom may be reduced.

The cost and time involved in dredging are considerable and there is also a problem with the disposal of the spoil/sediment - such sediments are not as useful as one might expect them to be. In the case of drainage channels and rivers, this waste material is usually dumped on the adjoining land and leveled. Fragments of vegetation, rhizomes, turions, and other propagules do tend to remain after management. Dredging, because it is expensive and slow, is commonly used only when a channel has deteriorated severely and other forms of maintenance are no longer effective, usually in conjunction with the removal of accumulated mud and other material.

Table 6.2 provides a summary of the productivity achieved using mechanical equipment for dredging irrigation and drainage channels.

4.3.3 Improving the efficiency of mechanical techniques

4.3.3.1 Timing

The season in which the control is effected is likely to alter the success of the operation. Plants with marked seasons for flowering and fruiting (e.g. the submerged weed *Najas* and the floating weed *Trapa*) or turion formation (e.g. the submerged weed *Hydrilla*) are best controlled before seeds or other types propagules are formed or shed. On the other hand, weed clearance on a regular basis can deplete the carbohydrate stores in perennating organs, effecting more lasting control. The prevailing weather conditions will dictate to some extent the time when control is undertaken especially when floating machines are used. The crop cycle also restricts the availability of labour and access into crops.

4.3.3.2 Improving the efficiency of existing machines and processes

More effort is needed to improve the efficiency of existing machines and processes and to reduce the cost of mechanical weed control. Every effort should be made to operate the machinery continuously and a good maintenance service with attendant resources is essential to this end. Particular attention should be focused on improving the efficiency of removing the plant material from the water body and the subsequent processing of harvested material. This may be reduced in volume and in weight by dewatering and through improvements in handling characteristics. The potential for the use of the cut material should be exploited.

The efficient use of any piece of machinery needs training and the acquisition of skill, a principle which extends to the maintenance of the machinery and reduction in down-time. More effort should be made to improve the training of personnel involved in such operations.

4.3.4 The development of new machines

The development of equipment for aquatic weed control lags behind the advances made in agricultural equipment, companies being inhibited by the restricted sales such machinery is likely to achieve. Nevertheless, new machines have been produced and interesting consideration has been given to the criteria which such plant should meet. In England, a National College of Agricultural Engineering study raised some fundamental ideas about the use of machines for controlling weed growth in drainage and irrigation channels from the banks (Murfitt and Haslam 1981). These were largely based on three premises.

1. The need to know the relationships between flow characteristics and the density, species composition, and physiological condition of the plants in the drainage channel. Mechanical control is seen not as a process of destruction but more as environmental management although such processes are very poorly understood.
2. The prediction of the reaction of the various species to cutting. This is only partially known and only for a few species.
3. Cutting is not necessarily the most effective means of controlling weed growth. It is based on agriculturally developed ideas and machines which themselves have developed to ensure the survival and regeneration of the cut crop. An improvement would be a machine or action which inhibited regeneration. This could include such actions as crushing and bruising especially roots or rhizomes, repeated chopping/cutting, drought, rolling, discing and damage due to alterations in the light regime.

4.4 Chemical control of aquatic weeds

4.4.1 Introduction

Herbicides can offer a cheap, effective, and rapid method of aquatic weed control. As a powerful tool in irrigation and drainage channel management, they require knowledge and understanding to be used safely and effectively. If misused, they can have side effects which may be harmful to aquatic organisms and, ultimately, to humans.

Most of the herbicides used in water bodies were developed originally for terrestrial use, so their basic behaviour and properties were already known before they were tested and adapted for aquatic use. Subsequent testing procedures have examined, in more detail, the toxicity to aquatic fauna, persistence and breakdown products in water and hydrosoil, effects on irrigated rate, susceptible weed species, and safety precautions required by the operator. Applications made without following these instructions can, at best, result in a poor level of weed control and, at worse, cause unnecessary damage to the target ecosystem. Even so, the user must decide the degree of weed control required in a particular body of water because overmanagement can be as harmful, in the long term, as undermanagement. The optimum level of control depends on the uses and priorities in each individual situation. A land drainage or irrigation channel may require total removal of aquatic weeds for the longest possible time, whereas in a channel also used as a fishery, reduction in emergent or floating weeds may be all that is necessary. Both of these extremes, and intermediate levels of control can be achieved by herbicides. The choice of the correct application method requires detailed knowledge of the capabilities and limitations of each herbicide. In many countries, government - or industry - sponsored training schemes are available which provide the user with both theoretical and practical experience of selecting and applying these herbicides.

Herbicides may have a direct toxic effect on non-target aquatic organisms or an indirect effect resulting, for example, from the removal of the target weeds. Laboratory-based toxicity tests often indicate greater toxicity than is found in the field. Thus they tend to err on the side of safety. Laboratory tests are followed by field experiments which can confirm laboratory results but may also show unpredicted toxic effects. By the time that the chemical receives official approval for aquatic use, the information available is such that direct toxic effects are unlikely to occur if the manufacturer's instructions are followed correctly. Some indirect effects are the inevitable result of the changes to the ecosystem caused by effective weed control. Thus, they are not limited to herbicides but can occur after any weed control operation. However, since herbicides can produce more thorough and, sometimes longer-lasting, control than other methods, the indirect effects can be more pronounced.

Several of the terms used to describe the behaviour and properties of herbicides cannot be defined absolutely because these properties vary under different conditions of use. For example, a herbicide may be termed 'selective' if it controls only a limited range of plant species. However, it may become 'non-selective' at higher rates of application.

The term 'active ingredient' (a.i.) refers to the concentration of herbicidally-active chemical within a formulation. It is expressed in terms of weight of active ingredient to volume (w/v: liquid formulations) or to weight (w/w: solid formulations), and may be shown either as grams per litre or percentage (e.g. the usual commercial formulation of glyphosate contains 360 g a.i. l^{-1} or 36 per cent w/v).

Herbicides may be selective (e.g. dalapon which controls grasses but not broad-leaved weeds) or non-selective (e.g. glyphosate which controls almost all green plants). Contact herbicides (e.g. diquat) kill only those parts of the plant on which they fall (usually, the foliage), but if sufficient damage is caused, the whole plant may die. Translocated herbicides (e.g. dichlobenil) are absorbed by one part of the plant but move within the plant and act on other tissues or growing points.

Persistent herbicides (e.g. fluridone) retain their activity in the soil or water for some time, usually measured in weeks or months. Non-persistent herbicides (e.g. glyphosate) act only when sprayed directly onto foliage and lose their phytotoxic activity very quickly on contact with soil or water. Some herbicides may show both characteristics; for example, diquat is non-persistent in an active form when sprayed onto terrestrial emergent plants. The droplets of chemical which miss the plant fall directly onto the soil and are rapidly and irreversibly absorbed onto soil particles, where they persist in non-phytotoxic form. In water, diquat molecules remain active in solution until they are absorbed by plant cells, or absorbed onto sediments. The term 'availance' is defined as the combination of residue concentration and period of residue persistence in the aquatic environment, which produces a phytotoxic effect on the target plants.

There are a number of herbicides suitable for the control of aquatic weeds varying widely in the range of species controlled, toxicity to fish, mammals and other life forms, persistence in the water and in the sediment, and the type of water in which the chemical will be effective. Some herbicides effect several plant families, i.e. many species, some effect only a limited group of species. There are also various ways of applying herbicides: spraying onto the foliage using a knapsack sprayer; distributing pellets into the water, and injecting into flowing water using an alginate formulation. Table 4.2 provides a useful summary of the range of herbicides and the types of plants they control. The label provided with the herbicide chosen for use will:

a. specify safety precautions to be observed by the operator;

b. state the interval of time to be observed between application and the use of treated water for irrigation of crops. Water intended for the irrigation of crops must not be treated with herbicides unless irrigation can be avoided for the period after treatment specified on the product label;

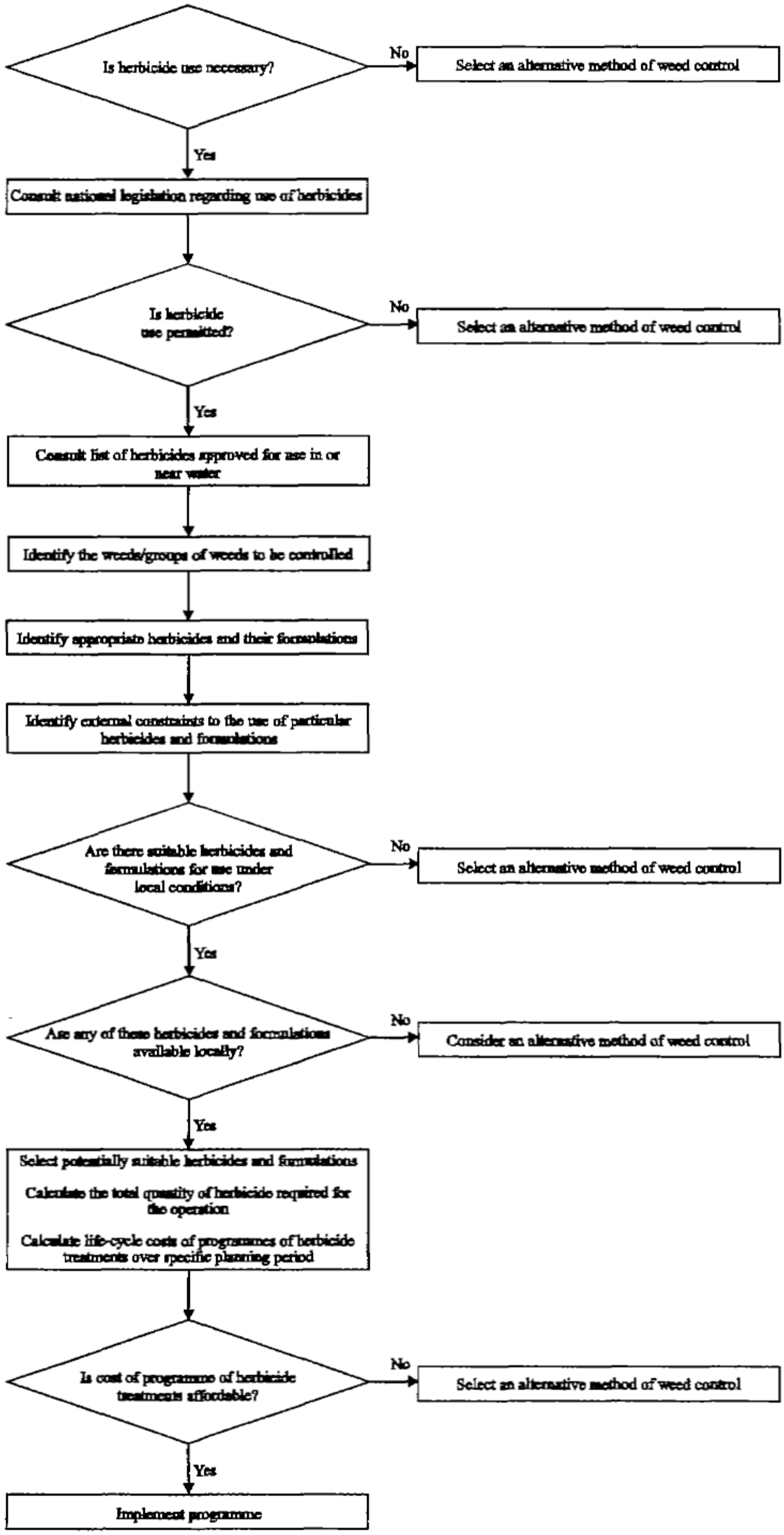
c. the range of species against which the chemical is effective;

d. provide detailed instructions on the use of the herbicide including the dosage to be used;

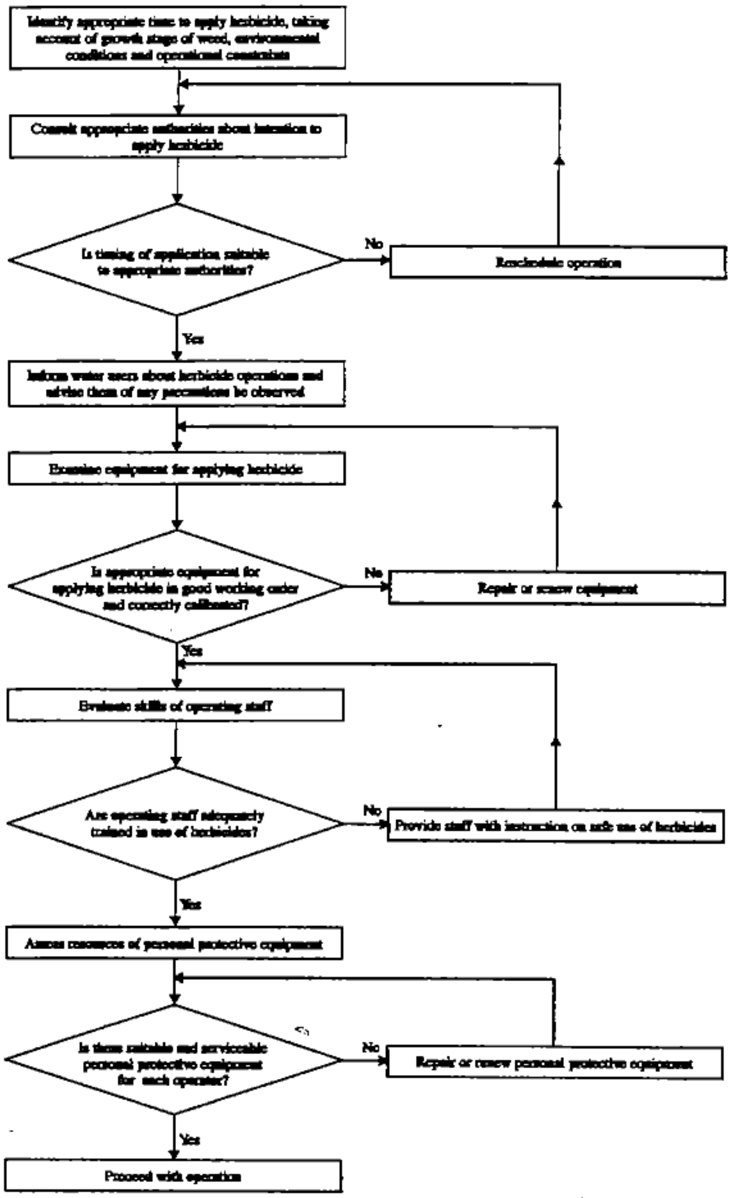
e. the conditions and means of formulation and application which should be used.

Flowcharts 1-5 in Figure 4.1 aid the decision whether or not to use a herbicide. Figure 4.2 provides flowcharts relating to the selection and preparation for use of herbicides.

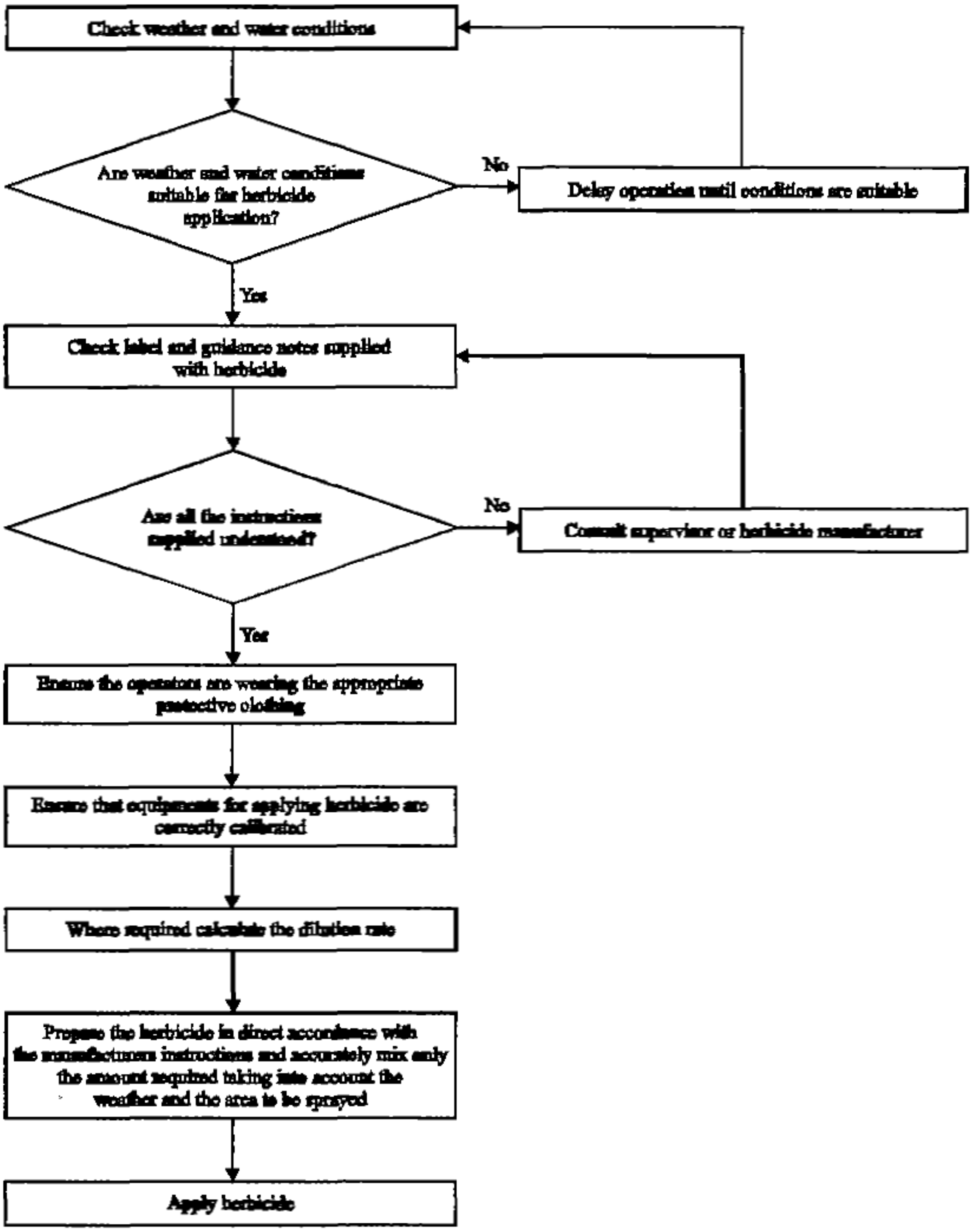
Figure 4.2. Flowcharts to aid the selection of and preparation for use of herbicides. Herbicides – Selection



Herbicides – Advance preparations for application



Herbicides – Preparations on day of application



4.5 Biological control

Biological control methods for managing aquatic weeds are based on the deliberate introduction or encouragement of a certain species which will restrict or prevent the growth of particular weeds. These species, or agents, can be herbivorous insects, mites, snails, fish, birds or mammals; disease agents such as fungi, or plants , e.g. trees, which shade and hence reduce aquatic plant growth.

Methods which could be considered for use in channels systems include:

a. herbivorous fish. Herbivorous fish (e.g. *Tilapia* and *Ctenopharyngodon idella*) have been proven to effectively control vegetation in irrigation and drainage channels. The grass carp (*Ctenopharyngodon idella*) does not normally breed outside its native China, nevertheless its introduction into a country or region would need to be considered carefully and appropriate steps taken to ensure approval of such a technique.

b. shading. Trees and floating aquatic plants can effectively provide shading such that other plant growth is inhibited. Such planting is best introduced early in the life of the scheme to enable maximum benefit. Trees need to be planted along those channels where shading will be most effective whilst minimising any impact on the crops (Plate 2.3). Wind direction can be used to minimise leaf accumulation in the channel. Such trees have other advantages including a harvest achieved through either selective cropping or fruit production, and shading for workers resting from their labours in the fields.

c. straw. The decomposition of straw in water has been found to release certain chemicals which stop algal growth and hence can prevent the build up of filamentous algae. The basis of the method is to put straw bails (either barley or wheat straw) into the water. These bails might inhibit flow in the channels and a stocking or sausage shape of packing the straw would be more appropriate. Although the technique has been used for a long time, its use on a planned basis for reliable algal control is only just being formulated.

There are significant advantages with biological control once it has been established, notably that the weed problem can be contained, e.g. using grass carp, with relatively little management input and hence cost. The disadvantage is that determining a biological control agent typically takes a long time and is not guaranteed to be successful. Herbivorous fish require a substantial investment in setting up and maintaining a breeding programme and the fish might be unsuccessful if they migrate out of the system or were caught by the local community as a food source. Using trees for shading is attractive but will take as long as is necessary for the trees to grow to maturity. More novel approaches, e.g. an introduced insect, need substantial research to ensure that sufficient damage will be done to control the weed but also to ensure that the introduced insect will not damage other plants, especially crops.

Biological control options are often regarded as the most environmentally friendly of control measures. This is not necessarily true. For example, overstocking with grass carp can lead to very turbid and eutrophic water, and trees established for shading can create problems through the accumulation of leaf litter in the channel.

4.6 Environmental and integrated control

Integrated control has been broadly defined as a management system that utilises all suitable techniques to reduce pest populations and maintain them at levels below those causing injury (van den Bosch *et al.* 1971). However, the term also refers to approaches aimed at minimising the use of pesticides (Coödinatiecommissie Onkruidonderzoek 1984), an alternative definition being a control system based upon the population of a harmful organism taking into account natural resistance factors and based upon a minimal use of techniques and products harmful to the environment.

The concept of integrated weed management is becoming more widely accepted and the approach is now being applied in irrigation and drainage management. This should include:

- careful irrigation water control to reduce drain discharge and thus facilitate control of weeds in drains
- minimising the movement and deposition of silt into and around the channels preventing the encouragement of excessive weed growth on accumulated sediment
- minimising the introduction of fertilisers and other nutrients into the water in the channels
- integrating harvesting of forage into the weed control programme

- preventing livestock from trampling down channel banks and hastening weed infestation.

As described at the outset of this chapter, it is unusual and unwise to rely on a single weed control method, e.g. only herbicides, or worse just one type of herbicide. A suite of methods is necessary typically combining manual, mechanical and environmental measures. The integration of such a range of techniques is important to ensure that they are effective and efficient.

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CHAPTER 5

MAINTENANCE POLICY

5.1 Introduction

Maintenance can be defined in general as "any activity that slows the deterioration of a facility, whether caused by use or ageing" or more specifically, "a management response to the deterioration of the physical condition of irrigation systems that threatens to make it impossible to achieve operational targets" (Carruthers & Morrison (undated) p14, from Ostrom *et al.* 1993 and Karunasena 1993).

Maintenance policy covers the following, which are described in turn in this chapter:

- what are the objectives of maintenance?
- what is to be maintained?
- how is maintenance to be executed?
- what is the required institutional set-up? (who will manage and execute maintenance?)
- how much budget is needed?

Maintenance policy as used in this book should be distinguished from the maintenance strategy and the maintenance programme, which are discussed in Chapter 6. Maintenance strategy is the way of implementing the policy. The strategy comprises a number of operations, each with a specified method and frequency (e.g. weeding secondary canals twice per year). The maintenance programme is the time-related schedule for undertaking these operations, with start and finish dates for each constituent task.

5.2 Aims, objectives, performance indicators and targets

This section addresses the question: what are the objectives of maintenance.

5.2.1 Aims of irrigation and irrigation management

The overall aim of irrigation will depend on the specific organisation responsible (for example ARDA or the National Irrigation Board in the case studies described in Chapter 2) or the scheme being considered (e.g. the Chisumbanje or Mwea schemes). Chambers (1988) suggests "optimising human well-being" to encompass the many different possibilities, but for our purposes it is helpful to expand this into the following typical aim for irrigation management:

Optimising human well-being by maximisation of agricultural benefits through the controlled delivery and removal of water, while safeguarding the environment, and by making efficient use of water and other resources.

Benefits may be enhanced by increasing the quantity or improving the quality of agricultural production. In order to do this, attention must focus on ensuring that:-

- the hardware of the system is in order to perform its hydraulic functions to the required standard.
- the distribution of water at the farm level is adequate, timely, equitable and reliable.

Both of these demand effective management of the irrigation system. Effective management therefore embraces

- the condition and serviceability of the hardware or physical assets
- the behaviour issue of irrigation management.

Crucial to both of these considerations is the role and performance of maintenance. Without maintenance, weed growth and siltation cause deterioration in the condition of the system, a reduction in hydraulic performance and a reduction in agricultural benefits.

System deterioration is a function of both age and use. Maintenance is needed to reduce the rate of system deterioration and its attendant costs in order that the net benefits of the system can be maximised. It is useful to think of benefits as including costs of poor performance avoided.

By prolonging and sustaining the life of capital equipment and infrastructure the probability of production loss is reduced. In irrigation the potential for production loss arises from:

- Shortcomings of the system in distributing water in both space and time to crops as required.
- Shortcomings in the timely removal of surplus water in accordance with crop needs.

Both shortcomings may be increased by failure of the system to perform to the target level of service as a result of weed growth or silt build up.

Inadequate maintenance may have the following adverse consequences:

- Production losses caused by failure to effectively deliver and remove water consistent with crop requirements. Both the quantity and quality of crops may be adversely affected.
- External diseconomies of production may be generated. These are unwanted and costly side-effects of production, for example salinity build-up in soils and water logging, often caused by inefficient drainage. They are the unintended consequences of poor maintenance, but such external costs are often ignored when the management or maintenance decisions are being made, and the costs are transferred to the future or to others.
- Introduction of inequities between farmers dependent on the system, manifested by conflicts (for example with respect to availability of water) and arbitrary redistributions of income. Not only may social disharmony result but also the care

of the system may be adversely affected. If the result of unfairness is demoralisation of some individuals the interdependencies inherent in irrigation systems may cause individual neglect to adversely affect the whole scheme.

5.2.2 Objectives for management of irrigation and drainage channels

The focus of this book is on the management of the irrigation and drainage infrastructure which is part of a wider system with the typical aim given above. Objectives will again vary with the situation and the overall aim and perspective, but we consider the following as appropriate objectives for the management of the irrigation and drainage infrastructure:

1. Adequacy and equity of the quantity and timing of water delivery and removal
2. Reliability (i.e. the stability of discharges and predictability of timing) and sustainability (i.e. the risk of breakdown) of water delivery and removal
3. Safeguarding the environment and public health
4. Efficient use of water and other resources

These objectives apply to both operation and maintenance activities. Weed management is usually undertaken as part of channel maintenance work, and is thus related to other activities such as desilting channels. Maintenance is undertaken to sustain the carrying capacity and integrity of the channel, prevent failure by a channel breaching or overtopping, and minimise losses from seepage or evapotranspiration (evapotranspiration losses from reservoirs may be reduced significantly by weed management). Weed growth tends to have a more rapid impact on the discharge capacity of a channel than siltation, and thus requires more frequent maintenance.

These can be considered as hydraulic, environmental and efficiency objectives, and these headings are used in the sections below for derivation of focused performance indicators and specific targets for the management of weeds in irrigation and drainage channels. The performance indicator is a measurable indicator of system performance, preferably one which can be easily monitored, e.g. the canal discharge. The target is the target level of the performance indicator, e.g. the scheduled discharge at the time. The level of service is the frequency that the performance meets the target.

5.2.3 Hydraulic targets for channel management

The management of weeds in irrigation and drainage channels can be analysed by using the concepts of hydraulic performance and condition.

5.2.3.1 Hydraulic performance

Objectives 1 and 2 (see Section 5.2.2) require the maintenance of irrigation and drainage channels to meet the following specific targets:

- The channel should be capable of conveying water at a predetermined target discharge, which varies during the year
- The water level at the required discharge should ensure a freeboard between water level and bank top level which equals or exceeds a predetermined target freeboard.

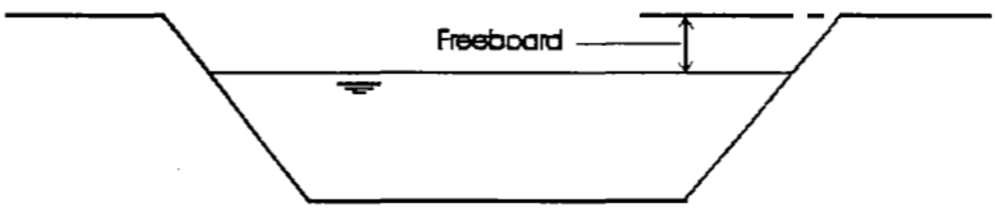


Figure 5.1 Schematic diagram showing canal freeboard

On many schemes the target discharge varies during the year with the irrigation requirements, depending on the crop calendar and climate. An example is given in Fig. 2.4 (Chapter 2) are from Mwea Irrigation Settlement Scheme. The target freeboard however would normally be the same throughout the year, to provide a safety margin against water over-topping the bank.

Thus, hydraulic performance can be represented quantitatively by the delivery performance ratio (DPR) and the freeboard ratio (FBR), defined as follows:

$$DPR = \frac{Actual\,Discharge}{Target\,Discharge}$$

$$FBR = \frac{Actual\,Freeboard}{Target\,Freeboard}$$

where freeboard is the difference between bank top level and water level.

For optimum performance at a particular time, DPR = 1 and FBR ≥ 1, these figures providing the target levels of the performance indicators.

Discharge data are commonly collected at regular intervals, enabling DPR values to be determined for corresponding times.

The actual freeboard at any time will depend on both the actual discharge, and the condition of the channel. Thus at those times of the year when the target discharge is low, a poorer channel condition can be tolerated as it will still pass the current target discharge at the target freeboard, that is optimum performance with DPR = 1 and FBR ≥ 1. Freeboard also varies with distance along each reach of the channel between structures, and will tend to be least at the upstream end of a reach, as the poor condition of a channel causes an increase in water slope. However freeboard is rarely measured, except as the water level at the downstream end of a reach, so FBR is a difficult indicator to determine. An alternative approach would be to set a tolerable failure rate as the target, for example the frequency of overtopping of a canal. This would be easier to monitor. We believe however that the FBR is the key indicator of risk of failure, and greater attention is needed to monitoring actual freeboard levels.

The question then arises: what should be the target freeboard? The design freeboard at design discharge includes allowances for wear and tear of the banks, and rises in water level due to unforeseen circumstances (such as increased discharge or deterioration in canal condition). Reduced freeboards are often observed on canals in practice, and it seems reasonable for the target freeboard at actual operating discharge to be less than the design freeboard at design discharge, which has to take account of the various uncertainties at the design stage.

The target freeboard should be derived from local conditions, taking account of these considerations. In general, a target freeboard of 60% of the design freeboard (with a minimum of 0.20 m) should be satisfactory, depending on local circumstances such as frequency of monitoring freeboard and the acceptable risk of failure. This is based on consideration of the formula often used to calculate freeboard for canals designed using the Lacey equations (in metric units):

Freeboard (design) = $0.2 + 0.235\ Q^{0.33}$;

eliminating the 25% surcharge on discharge and reducing the fixed freeboard by 0.10 m gives a formula for target freeboard of

Freeboard (operating) = $0.1 + 0.15\ Q^{0.33}$.

Trial calculations give values of Freeboard (operating) of about 60% of Freeboard (design). Similar results could be expected with other methods of determining design freeboard.

5.2.3.2 Condition

The weed-related condition of the channel can be represented by its weed succession stage, as described in Chapter 3 (Figure 3.5). Weed clearance changes a channel from a 'poor' to a 'better' hydraulic condition by returning it from a late to an earlier stage of succession. The silt-related condition can be represented similarly, but siltation normally occurs over a longer timescale, requiring less frequent clearance. Desilting operations remove weed, including root material, at the same time as sediment, thereby returning the channel to an earlier stage of succession than would some, if not all weed clearance operations.

Several researchers have studied the effect of weed growth on channel roughness and hence hydraulic performance through laboratory and field studies. This has shown that the commonly used Manning roughness coefficient (n) varies inversely with the flow velocity and hydraulic radius in a vegetated channel, which complicates the analysis (see Section 3.7.1). Also the generalised models from laboratory work use physical measures of weed infestation which are difficult to measure in field conditions, for example the fraction of channel cross section occupied by weed (Kouwen *et al.* 1969) or deflected weed height (Kouwen and Unny 1973). These models have been used for research in Europe (for example in detailed field and modelling work by Querner, (1993)), but our field experience showed that it would be unrealistic to adopt them as the basis for practical procedures to be followed by irrigation staff, particularly where technical skills are limited. Therefore our work is focused on condition categories as described below.

Another possible indicator is the Discharge Capacity Ratio (DCR) of the channel. This represents the discharge which the channel would pass in its current state (current weed infestation and degree of silting) when flowing at the target water level (allowing for the target freeboard), compared to its target discharge capacity (or design discharge of the channel)

$$DCR = \frac{Actual\ Discharge\ Capacity}{Target\ Discharge\ Capacity}$$

The DCR is useful as an indicator of the current condition of the channel, especially as target values could be set easily for different periods of the year, related to the irrigation requirements and irrigation schedule.

Measurement of DCR however requires the channel to be operated at the target water level. Our research showed that channels are often operated at other levels, and it is difficult to derive DCR values from measurements in such cases. What would be possible however is a subjective grading system, with grades being allocated by judgement of field staff from their experience, for example:

Grade	DCR
A	75 to 100%
B	50 to 75%
C	25 to 50%
D	0 to 25%

Estimated DCR grades such as these are coarse and subjective, but may still be sufficiently accurate for monitoring the condition of each channel in a scheme, and programming maintenance work. The DCR reflects the overall condition of the channel, which combines the silt-related condition, the weed-related condition and other factors such as the structural condition of the banks. The weed-related condition of the channel may also be described by its succession stage and standard botanical survey measures (particularly the percentage of plan area covered by each species) as described in Chapter 3.

Box 5.1 The relationship between discharge, freeboard and roughness

Example: A secondary canal is designed for a discharge (Q) of 0.900 m^3/s, with Manning's n = 0.030. The design cross section is bedwidth 1.50 m, water depth 0.75 m, sideslopes 1:1.5.

Assume weed growth causes the roughness n to double to 0.60, then

(1) If the water level remained the same, the discharge would halve to 0.450 m^3/s (DCR = 50%).

(2) If the discharge remained constant, the water level would rise by 0.31 m (assuming n remains constant).

A typical design freeboard, Fb(design), would be 0.50 m for this size of canal, so the water level would be only 0.19 m below the design bank top level, and in danger of overtopping at any particular low point (for example due to inaccurate construction or subsequent wear and tear or damage). The danger will be acute if siltation has raised the bed level, or any unforeseen event occurs such as a blocked gate downstream or closure of an offtake.

(3) If we adopt a target freeboard Fb(operating) = 0.60 x Fb(design)

= 0.60 x 0.50

= 0.30 m

then the maximum discharge will be 0.720 m^3/s (DCR = 80%).

5.2.4 Environmental targets for management of irrigation and drainage channels

The objective of safeguarding the environment and public health when managing weeds can be considered as follows:

- the selected weed management methods should be benign in their effects on the aquatic environment, apart from the target weeds
- weed management practices should minimise risks to the individual.

5.2.4.1 Effects on the aquatic environment

In addition to achieving the hydraulic objectives for a channel, the management adopted should not have an adverse impact on the environment (except for aquatic weeds). The most likely effects are those on the aquatic habitat. Weed management might have an unacceptable effect on such aspects as:

- human use of the water for drinking or bathing
- harvesting of certain species, e.g. fodder for livestock, reeds for basketry or door screens, aquatic plant roots for human consumption
- use of water for irrigating crops
- use of the channel for livestock watering
- fisheries resources
- rare or endangered species known to be present in, or using the channel

Impacts could occur through the misuse of herbicides or through cutting vegetation at inappropriate times. Vegetation left in the channel either after cutting or chemical control will decompose using up oxygen in the water which can have adverse effects on fisheries and other forms of aquatic life, and can produce smells and tainting in the water.

These effects can impact on the particular channel managed but can also spread on through the system and could be of significance downstream of the area, e.g. herbicides which might get into a river system receiving drainage from the irrigated area.

In a similar way to the setting of performance indicators by which hydraulic objectives can be evaluated, procedures need to be established by which the impact of weed management can be assessed. These could be as simple as designating certain sections of channel as potable water source supply or bathing areas or more complicated, foe example by linking these uses into certain time periods, e.g. the use of certain sections of channel for stock watering over fixed periods of the year. Where herbicides are used, the instructions on the label will specify time periods after application during which the chemical must not be used for irrigation purposes. In the case of a fishery, the permitted concentration of herbicide in the water should not be exceeded by ensuring that the correct dose is applied in the first instance. Regardless of the latter, permission to apply a herbicide must always be sought from the appropriate authority and guidelines/regulations followed.

5.2.4.2 Effects on the individual

The use of cutting tools, machinery and chemicals for weed control all pose a risk to the individual. It is essential to draw up safety guidelines for all these techniques including maintenance of tools, fitting of appropriate safety screens on machines and the type of protective clothing which should be worn. These are usually laid down for machines and herbicides (e.g. MAFF, 1995) but may need to be modified for use in certain locations. In-house safety guidelines will need to be written for most manual weed clearance techniques. These need to recognise the hazards of working along channels (e.g. snakes) and of entering the water (e.g. schistosomiasis).

The guidelines used for weed management need to be compatible and integrated within other health and safety guidelines and regulations as laid down by the irrigation authority.

5.2.4.3 Environmental enhancement

As well as ensuring that environmental objectives are met in terms of minimising adverse impacts and ensuring high standards of health and safety, the opportunity should be taken where possible to enhance the environment from both human and ecological viewpoints. This relates in particular to diseases such as schistosomiasis and malaria.

5.2.4.3.1 Mosquitoes

Malaria is common throughout tropical and subtropical regions and it transmitted by mosquitoes. Other diseases such as dengue fever, yellow fever, filariasis and certain types of encephalitis are also transmitted by mosquitoes. The eggs, larvae and pupae of mosquitoes are aquatic feeding and breathing at the surface of the water, and they can use irrigation and drainage channels so long as the flow is not too great. The larvae are protected from predators by aquatic plants and weed control measures may, therefore, assist in the control of the diseases which they transmit (e.g. Angerelli and Beirne 1982).

Mansonia mosquitoes which are responsible for transmitting rural filariasis and encephalitis, are unique in that both larvae and pupae derive their oxygen by puncturing air chambers in plant stems and roots by means of a specialised air tube. For example, two species of *Mansonia* are reported to be totally dependent on the free-floating aquatic weed *Pistia stratiotes* (Gangstad & Cardarelli 1990). As a consequence *Mansonia* mosquito breeding can be controlled by the elimination of all aquatic vegetation used by the mosquitoes. *Mansonia* numbers are directly proportional to the maintenance of a uniform and constant depth of water. Causing the water level to fluctuate or allowing the water body to dry out is very effective in reducing the numbers of larvae which usually take a considerable time to build up after the channel has refilled (Gangstad & Cardarelli 1990).

5.2.4.3.2 Aquatic snails

There a number of diseases caused by trematode worms that are parasitic in humans and for which aquatic snails provide an intermediate host. These diseases include schistosomiasis (bilharzia), paragonimiasis, clonorchiasis and fasciolopsiais, the former being one of the most important public health problems of the tropics and subtropics. Investigations have shown that there is a positive relationship between schistosomiasis-bearing snails and aquatic vegetation, for example in Egypt (van Schayck 1986) and in Puerto Rico (Ferguson 1980). Aquatic weed control not only removes the habitat for the snails but increases the likelihood of snails being controlled by omnivorous fish (Coates and Redding-Coates 1981).

5.2.4.3.3 Ecological stability

Channel systems in countries such as the Netherlands and England have become important refuges for a wide diversity of aquatic plant and animals species such that some areas have become designated as nature reserves. Consideration should be given to maintaining this diversity in irrigation systems, for example, by limiting management to that which is essential and recognising the importance of processes such as succession in maintaining this diversity. There can be practical advantages to this, following the school of thought which argues that diversity is directly related to stability. A stable irrigation system is much easier to manage than one which fluctuates, for example, in terms of the species which present themselves as problems. Diverse systems are also less likely to be invaded by alien species such as the free-floating aquatic weed *Eichhornia crassipes*. Ecologically sound weed management can also enhance fisheries output, for example, by providing suitable spawning vegetation in secondary channels.

5.2.5 Efficient use of resources for management of irrigation and drainage channels

The objective of efficient use of water and other resources requires systematic monitoring of operation and maintenance with the collection and analysis of appropriate data. The following are proposed as the basis for weed management to contribute to this objective:

- water losses from spillage, evapotranspiration and water control problems should be controlled at an acceptable level;
- the adopted methods for aquatic weed management should be chosen by comparing the use of resources of all possible methods which have similar outcomes.

These are discussed in turn.

5.2.5.1 Control of water losses

Control of water losses is a major concern of irrigation managers, and depends on the operation as well as the maintenance of the system. Inadequate weed control leads to increased losses of water through:

- spillage of water due to reduced channel capacities
- excessive evapotranspiration from weeds in intermediate reservoirs
- leakage through animal holes and inoperable structures.

These losses occur at all levels in the irrigation system, and the key to controlling them is regular measurements of flows in the various types of channels, and analysis to monitor the efficiencies of the channels. Current efficiencies can then be compared from systems world-wide have been collected by Bos and Nugteren (1990). The seepage of water through control structures can be sufficient to sustain aquatic weed populations which would otherwise have been destroyed by drying out of the channel.

5.2.5.2 Selection of efficient maintenance methods

We consider the use of resources by:

- ensuring the maintenance programme is based on the availability and efficient utilisation of physical resources such as labour and equipment (see Chapter 6)
- considering the cost of resources, and hence the cost of the programme: for a given maintenance level the minimum or least cost maintenance programme should be employed, as described in Chapter 7 (see also the Section 5.6).

5.3 Inventory

This section addresses the question: what is to be maintained?

Keeping the irrigation system in good order requires attention to:

- System components such as canals, drains, reservoirs, structures, embankments, access roads and paths.
- Equipment used in the maintenance programmes, including tractors, excavators, specialist buckets and other attachments, cutters, boats, chemicals, chemical applicators and a wide array of tools.
- Equipment needed to maintain the above mentioned assets. These include service and maintenance bays and their support tools.

For systematic maintenance of these assets it is necessary to list and compile summary information in asset registers which are updated regularly.

Although all of these assets are critical to the maintenance process, the concentration in this report is on those components which are critical to the performance of the hydraulic functions of the system. These functions are most imperilled by weed and silt formation and therefore the focus is on control of the water delivery system and the assets required to support that control. Maintenance of other civil works and roads is not central to this focus, but reference could be made to the books by Hindson (1983) and Coukis (1983). For the system components it is necessary to identify the types and sizes of channels to be maintained, and their extent (i.e. length) in order to decide on suitable maintenance methods, institutions and budgets.

5.4 Types and timing of maintenance

This section addresses the question: how is maintenance to be executed?

5.4.1 Maintenance categories

Maintenance can be considered in four categories (based on Sagardoy, 1982 and Burton, 1995):

(1) Routine preventive and minor maintenance
(2) Routine planned maintenance
(3) Special maintenance and emergency repairs

5.4.1 Maintenance categories

Maintenance can be considered in four categories (based on Sagardoy, 1982 and Burton, 1995):

(1) Routine preventive and minor maintenance
(2) Routine planned maintenance
(3) Special maintenance and emergency repairs
(4) Deferred maintenance

5.4.1.1 Routine preventive and minor maintenance

Routine preventive and minor maintenance is small maintenance work that is done on a regular basis by an individual labourer, without being included in a formal maintenance programme. Such work might include:

- monitoring the presence of problem weeds in channels and elsewhere in the river system,
- selective weeding of problem weeds at early stage within canals and drains from embankments (e.g. trees and bushes likely to cause damage) and from around structures
- frequent light operations to control weeds before flowering or seed set.

This work would normally be done by a water bailiff or gatekeeper, a maintenance labourer, or individual farmers (particularly within the tertiary unit). It may be very effective in reducing weed problems and reducing the amount of planned maintenance required.

5.4.1.2 Routine planned maintenance

Planned maintenance is larger-scale work which is identified as needing to be done, and included in a routine maintenance programme. This work is generally too big for one person to do and will be done by a group of labourers or farmers working together, or by mechanical equipment. The tasks may be undertaken by the irrigation scheme management agency using its own resources of equipment or direct labour; or alternatively the work may be let to a contractor, or done by farmers. Such work might include deweeding or desilting a complete canal or drain using labour-based, mechanised or other methods referred to in Chapter 4.

At Mwea Irrigation Settlement Scheme, weed clearance is scheduled two or three times per year, and desilting once per year, as described in Chapter 2 and detailed in Table 2.4. The maintenance records for 1992, shown in Figures. 5.2 and 5.3, indicate that the peak period for canal maintenance was May to July, and for drain maintenance, July to October. The records show that the allocation of labour and hydraulic machinery is consistent with the reported priorities of the management cycle, together with ongoing year-round activity on both canals and drain; these are related to the other weed clearance operations scheduled during the year and the need to make balanced use of the available resources of labour and hydraulic machinery.

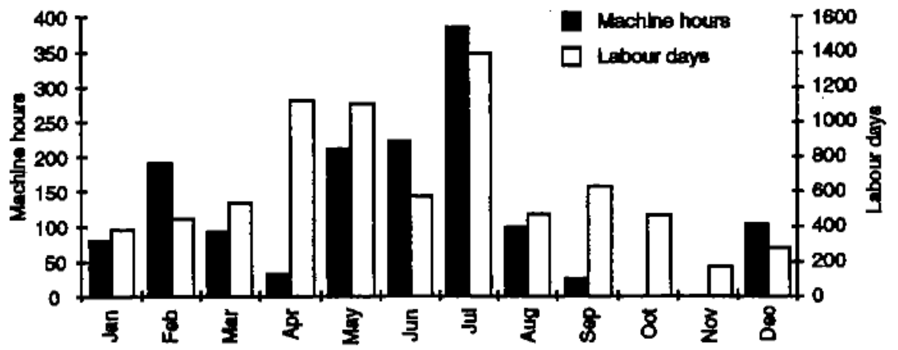


Figure 5.2 Canal Maintenance Inputs at Mwea Irrigation Settlement Scheme, 1992

Figure 5.3 Drain Maintenance Inputs at Mwea Irrigation Settlement Scheme, 1992

Inspection and monitoring of maintenance needs is part of the water bailiff's daily routine. Gatekeepers, pump operators and labourers will also be responsible for identifying and reporting maintenance requirements. Engineers or other operation and maintenance staff can then confirm and quantify the requirements, and their duties should also include formal inspections of the irrigation and drainage systems, and reporting on their condition. This may be carried out at regular intervals during the year, or annually. It is common to have periods of canal closure, one period for inspection, the other, longer one for annual maintenance. Ideally this should be scheduled for a time when there is little need for irrigation and when the weather conditions are most favourable (i.e. avoiding periods when it is too wet or too hot to work). The canal closure and draining down of the system will enable detailed examination of the works below the water line.

5.4.1.3 Special maintenance and emergency repairs

Special or emergency work is carried out as the need arises, following unforeseen problems such as dangerously high water levels in a canal or local flooding. Depending on the nature of the work it may be carried out by the irrigation agency, often with the assistance of the local population, or by groups of farmers.

This work might include unscheduled weed clearance to improve canal capacity and reduce the risk of failure, or temporary repair to canal embankments in the event of overtopping.

By its nature emergency maintenance work has to be carried out quickly. In systems where such needs are common (for instance in high risk flood areas) procedures need to be clearly established beforehand, and agreement reached with farmers and others on such procedures. An effective telecommunication system can be invaluable in such circumstances, for example if a canal breach occurs a message can be radioed to the headworks to close down or reduce the intake discharge.

5.4.1.4 Deferred maintenance

Deferred maintenance is maintenance work that has been identified as needing to be done but which cannot be done straightaway due to limitations of funds, limitations of manpower, or because it is not a serious problem at the present phase of the agricultural cycle, or other tasks have higher priority.

Such work might include any of the examples of planned maintenance given above, such as desilting canals or clearing of weeds from drains. Deferring maintenance may lead to future problems, requiring emergency repairs or rehabilitation of the system.

5.4.2 Implications for maintenance policy

Maintenance may be the *ad hoc* response to failure of system components, i.e. reactive, largely undertaken as special maintenance or emergency repairs. Viewed in this way it is often an element in crisis management. Maintenance will largely be of a corrective nature - putting things right after they have gone wrong. Given the randomness of component failure it is difficult to plan for the future under such a regime, spares may be unavailable or labour may be occupied on say competing agricultural activities. Because of these uncertainties the economic costs are likely to be large due to system failures and equipment downtimes.

Some of these uncertainties and their accompanying costs may be removed (or at least reduced) by a more proactive attitude to maintenance. This attitude anticipates things going wrong unless preventative measures are taken. Taking appropriate measures requires a planned, forward-looking approach to such issues as identifying potential weak and vulnerable links in the system and anticipating the resource requirements to prevent failure.

Planned maintenance involves the programming of work. Identification of specific tasks and maintenance outputs facilitates target setting, monitoring of performance and the provision of incentives for workers. Because of its proactive nature it requires routine inspection, servicing and preventive maintenance, replacement when appropriate and necessary remedial works.

Box 5.2 Benefits of maintenance planning

1. The principle benefit is that planned maintenance fosters and promotes a culture of caring for the smooth and efficient operation of all aspects of the system. It elevates the idea of system performance.
2. Maintenance can be phased through time to be compatible with the hydraulic requirements of the agricultural year if it is planned rather than a response to failures. The sequence of the agricultural cycle is critical in maintenance planning.
3. In the case of maintenance equipment higher utilisation levels may be achieved as downtimes are reduced. Higher productivity manifests itself in reduced costs. In the case of infrastructure better hydraulic performance may improve crop quantity and quality resulting in higher system benefits.
4. Systematic maintenance may reduce the incidence and costs associated with the aforementioned external diseconomies of production for example, salinity problems caused by poor drainage or excessive water use through over-topping.
5. Requirements of spare parts, tools and skills can be estimated and stocks of each maintained and employed at adequate levels. Elimination of wastage through holding surplus spares of redundant materials may be accomplished. A more systematic inventory policy may reduce the financial penalties of delayed receipt of spares.

Although it may be argued that planned maintenance is expensive in terms of resources and organisation, with sound institutional arrangements these expenses could be financed from the improved system working and the consequent additions to net revenue. It may equally be argued that without planned maintenance the potential economic losses are also considerable from system breakdown, more expensive repairs and poorer performance.

5.5 Maintenance management

This section addresses the questions: what is the required institutional set-up? And who will manage and execute maintenance?

The institutional model that we work from has three levels

- senior management of the irrigation agency, such as the Board of Directors of a company or parastatal or the Directorate of a government Department of Irrigation
- management and staff of each irrigation scheme
- farmers, both as individuals and groups, possibly organised in water user associations.

In addition central agency staff may be involved (for example, in procurement) and some work may be undertaken by contractors. An important issue is the split of responsibilities between the various levels and organisations.

Senior management of the agency will be concerned with maintenance policy. The planning and implementation of the maintenance programme will be the responsibility of scheme management and/or the farmers.

Economies of scale in the provision and maintenance of mechanical equipment require major maintenance tasks to be controlled and executed at the scheme (or agency) level. Economies of scale arise from the spreading of fixed costs (e.g. maintenance depots, equipment and staff); a related issue is the indivisibility of mechanical plant - it cannot be divided into farmer size units and for example the minimum size of excavator may be much larger than an individual farmer could afford or need. Also better terms for the purchase of inputs, for example fuel and lubricants, spares and loans may be obtained by large scale purchase.

Moreover, the complexity and the interdependencies in irrigation systems require an overseeing authority at least for the maintenance of higher order components of the system. Synchronising maintenance timings to the deployment of capital equipment and labour are obvious examples of the need for a supervisory agency. There are other reasons which relate to the economist's point of view that a maintenance service has the characteristic of a collective or public good. These are goods which once provided are consumed by all - even those who do not pay. Markets do not function for these goods and markets fail to allocate them. In the absence of some element of compulsion they will not be provided or will be provided at sub-optimal levels. Other examples, include street lighting, swamp drainage for malaria control and refuse removal. Collective action is needed to provide the public good at an efficient level and this requires a body such as the scheme management to levy compulsory payments and to supply maintenance at least at the primary and secondary levels.

Maintenance of smaller channels is commonly left to farmers perhaps with supervision by the scheme management. However, the interdependencies in systems at the lower levels demand that checks on maintenance quality are made and that sanctions can be imposed on poor maintenance provision. At the farmer level the incentives may be perverse in that poor maintenance may even confer benefits for the offender (i.e. they may get more water) while the costs are imposed on a neighbour downstream (i.e. they may get less water). Thus an overseeing authority must be able to deploy incentives and sanctions to ensure that such perversities are overcome. This may be accomplished, for example, by making a private benefit to the farmer conditional upon a satisfactory level of maintenance. Hence, free or subsidised seeds, tools or technical advice may be contingent on passing a maintenance quality check.

The scheme management should also have the function of arbitrator in the event of disputes between neighbours. These may occur for example when a tertiary channel is bordered by the land of two farmers who fail to agree on a division of maintenance responsibilities.

5.6 Maintenance budget levels

This section is concerned with the question: how much budget should be allowed?

From an economic perspective, maintenance expenditures are viewed as investment expenditures rather than as consumption expenditures. Money and resources are used to assure a return through the increase in net benefits that the well-maintained system provides.

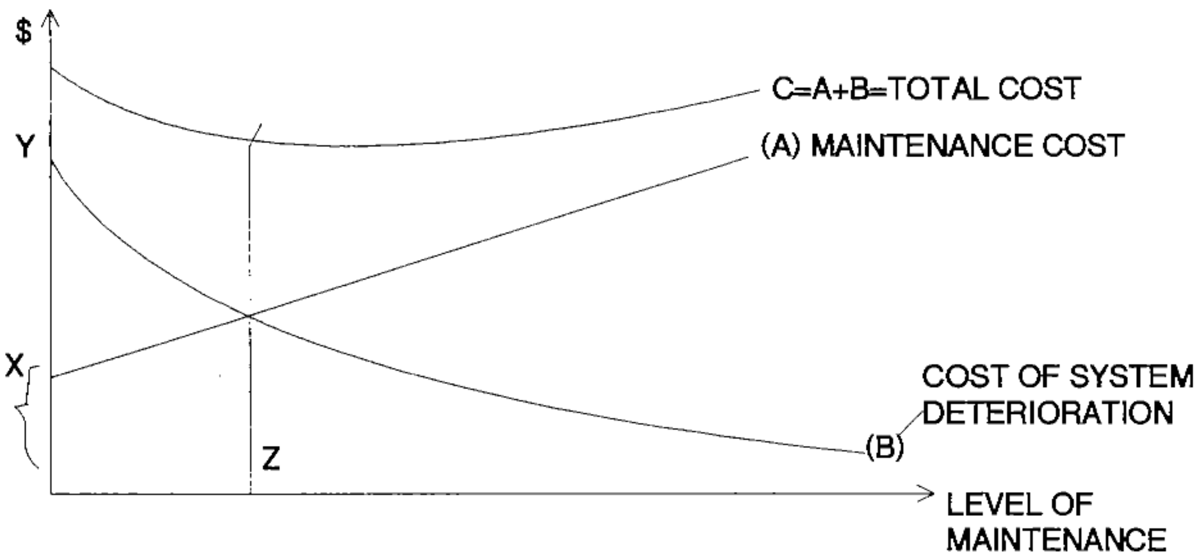
The relevant judgement for management is whether the incremental maintenance expenditures needed for a level of maintenance are more than recovered by the benefits which ensue in the form of avoided deterioration costs (see Box 5.3). In making this judgement it is important to realise that maintenance is forward looking. Expenditures that have been made in the past and which are now sunk costs are irrelevant for current decisions. Thus, an expenditure incurred 10 years ago for the acquisition, say of a hydraulic excavator, has no significance for today's decision as to which is the least cost method of removing silt. The issue is whether future incurred costs provide sufficient benefits to justify their future expenditure.

Operationally, it is difficult, if not impossible, to estimate the money value of benefits in the form of avoided reductions in the quantities and qualities of crops which inadequate maintenance would cause. The calculation is complicated because neglect of maintenance only increases the probability of losses but does not make them certain. External events may compensate for poor maintenance, for example, more plentiful rain than usual or the introduction of less water dependent crop varieties.

Because benefits are location and crop specific and their monetary estimation requires a large amount of information, it is suggested here that a more workable way to proceed is to examine alternative maintenance programmes and to calculate the minimum cost strategy for attaining a given level of system performance. The latter is deemed to be a standard of weed and silt clearance sufficient to reduce the risk of economic losses to acceptable levels. The mechanics of this calculation and examples are provided in Chapter 7.

Box 5.3 The idea of optimum maintenance provision

From economic principles the maintenance budget should be set according to the benefits obtained from maintenance, and the diagram seeks to show the principles which govern the idea of optimum maintenance. The vertical axis provides an indication of costs measured in money. The horizontal axis shows the level of maintenance. In the case of a stretch of canal it presents the amount of clearance.



The amount of X could be viewed as the minimum expenditure without which the irrigation system would completely fail to function. As clearance effort increases, timely and sufficient quantities of water reach and leave the crops. Additional clearance requires resources - labour and excavator time - and so Curve A rises from left to right. Failure to maintain the system resulting in complete collapse would impose economic costs equal to Y amount. As clearance effort increases the expected cost of system deterioration costs include financial losses due to lower crop yields and perhaps reduced quality. In addition the economic costs of wasted water should be included. Although many irrigation authorities do not pay for water or pay a price below cost, the economic value of this water is not zero but the Average Incremental Cost of its production.

The vertical sum of Curves A and B yields the Total Cost Curve C. It is tempting to say a perfectly maintained system should have zero deterioration but this could only be achieved at exorbitant cost.

Taking both maintenance costs and the avoided costs of deterioration (the benefits) it can be seen that the economic optimum degree of clearance is at the minimum of Curve C at level Z.

In practice the curves are difficult to define due to lack of data, particularly on the cost of system deterioration. The important point to note is that there is an optimum level of maintenance which is usually neither the minimum to prevent collapse of the system, nor the amount which enables maximum performance, unaffected by deterioration in the condition of the system. Without the data, managers have to make a judgement of this optimum level of maintenance, by asking questions like "is it worth doing any extra maintenance work?".

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CHAPTER 6

PREPARATION OF A MAINTENANCE PROGRAMME

6.1 Introduction

A maintenance programme for an irrigation system consists of a schedule of maintenance operations to be undertaken on specific irrigation and drainage channels at specific times, using specified resources.

Figure 6.1 shows our recommended approach to the preparation of a maintenance programme for an irrigation and drainage system. It consists of five stages:

1. Establish a maintenance policy, including target levels of service
2. Identify maintenance strategy options to deliver the target levels of service. Each option will usually be a combination of desilting and weed control operations, each with a specified method and frequency.
3. Prepare a balanced programme and resource allocation for each option, to make efficient use of the resources while meeting the targets
4. Select the optimum maintenance strategy and programme from the options, to minimise the life cycle cost over the planning period
5. Prepare a detailed work programme for the optimum maintenance strategy.

Stage 1 has been described in Chapter 5, stages 2 and 3 are described in this chapter and stages 4 and 5 are considered in Chapter 7.

6.2 Maintenance strategy options

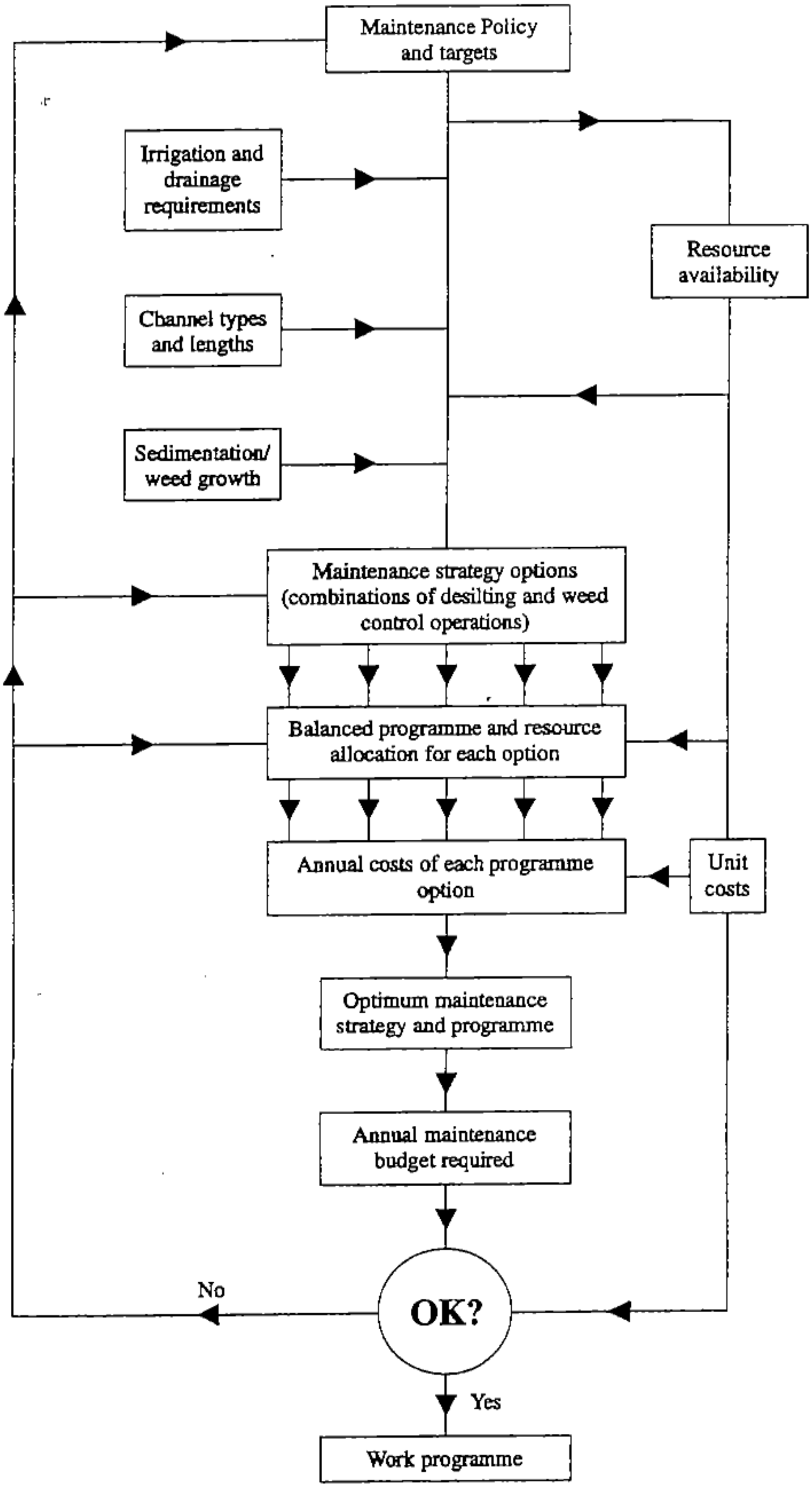
The time schedule of the maintenance programme is essentially governed by the cycle of activities in the agricultural year (e.g. Figure 2.4). For a particular crop, water requirements demand the timely and efficient supply and removal of water through different channel systems (canals and drains) requiring different timings and methods.

The differences in crop water demands through the year are also sometimes a constraint on maintenance activities but may also provide opportunities for maintenance. Effective managers are adept at exploiting these windows of opportunities (e.g. when channels are dry in Chisumbaiye Scheme, see Section 2.3.1.5).

Physical conditions which are frequently encountered in tropical or sub-tropical climates such as water turbidity and climate favouring rapid vegetative growth may dictate more frequent weed cutting and desilting than in similar systems in temperate climates. Failure to maintain the systems adequately may cause:

- more rapid deterioration of assets than in more temperate climates
- a reduction in the productivity of postponed maintenance which will be translated into higher costs per unit of clearance achieved - a machine will achieve less clearance per hour when assets are in an advanced state of deterioration.

Figure 6.1 Preparation of a maintenance programme for irrigation and drainage channels



Increasingly the nature of the maintenance activity is likely to be determined by ecological and health factors. The sensitivity of animal or human well-being may preclude some maintenance activities whilst promoting others.

In each situation there will be various possible options for a maintenance strategy which will deliver the target level of service. Each strategy option will be a combination of desilting and weed control operations, each with a specified method and frequency for each type of channel. The issues to be considered are shown in a flow chart in Figure 6.2, and explained below. (The terms maintenance policy, strategy, operations and programme are used as described in Chapter 5.)

The various feasible maintenance strategy options can be viewed as alternative investment projects, each characterised by different capital costs, operation and maintenance costs and environmental effects. An array of methods is available to control weeds in irrigation and drainage channels (see Chapter 4), and these can be combined in various ways as maintenance strategy options. These may include combinations of capital (e.g. hydraulic machinery) and labour (e.g. manual cutting). Alternatively, the input mix may be of machinery and herbicides, labour and herbicides, or include environmental or biological control. In many instances, technical and economic considerations constrain the practical application of the available control strategies.

6.2.1 Resource availability

It will be important to establish early in the programme planning which resources are available during each period of the year and whether there is any flexibility to buy in extra resources, e.g. casual labour and hire equipment, or to use resources elsewhere when not required for maintenance, e.g. mechanical equipment used for construction. These resources may include any or all of the following: a labour force, handtools, mechanical equipment, herbicides and biological agents. Any resource constraints will influence the feasibility of various desilting and weed control methods.

6.2.2 Setting channel capacity and condition targets over the annual cycle

Engineers are accustomed to specifying target discharges for each period in the annual cycle, varying with the irrigation and drainage requirements. For management purposes it will often be convenient to express these as percentages of the design discharge capacity of the channel, and an example is shown in Figure 6.3. These figures represent the minimum required Discharge Capacity Ratio (DCR) in each period, as described in Chapter 5.

The actual DCR of the channel in each period will depend on its silt-related and weed-related condition, and a judgement can then be made of the equivalent required condition for each period (for example, for each month). The weed-related condition could be expressed in terms of weed succession stages or percentage cover, as described in Chapter 3.

Figure 6.2 Development of maintenance strategy options

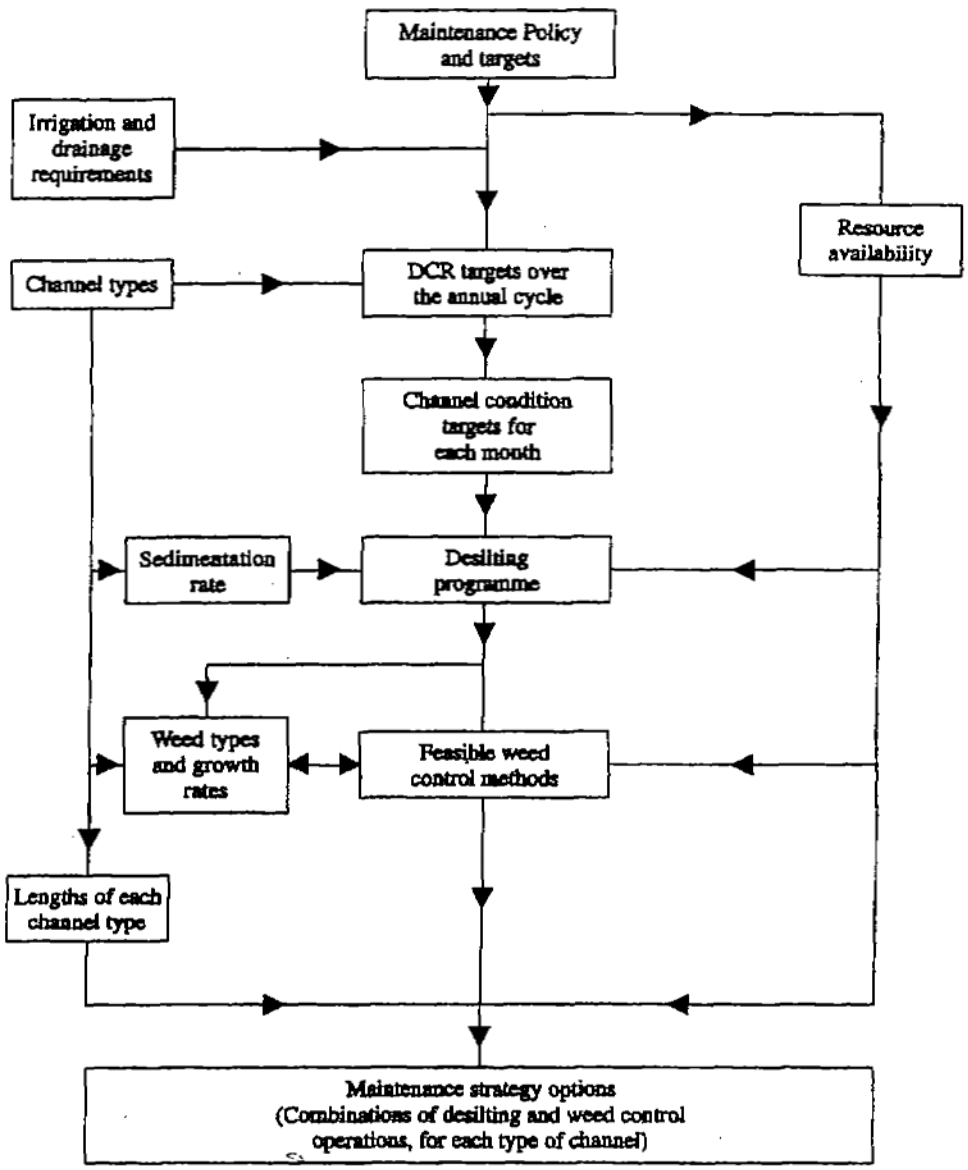
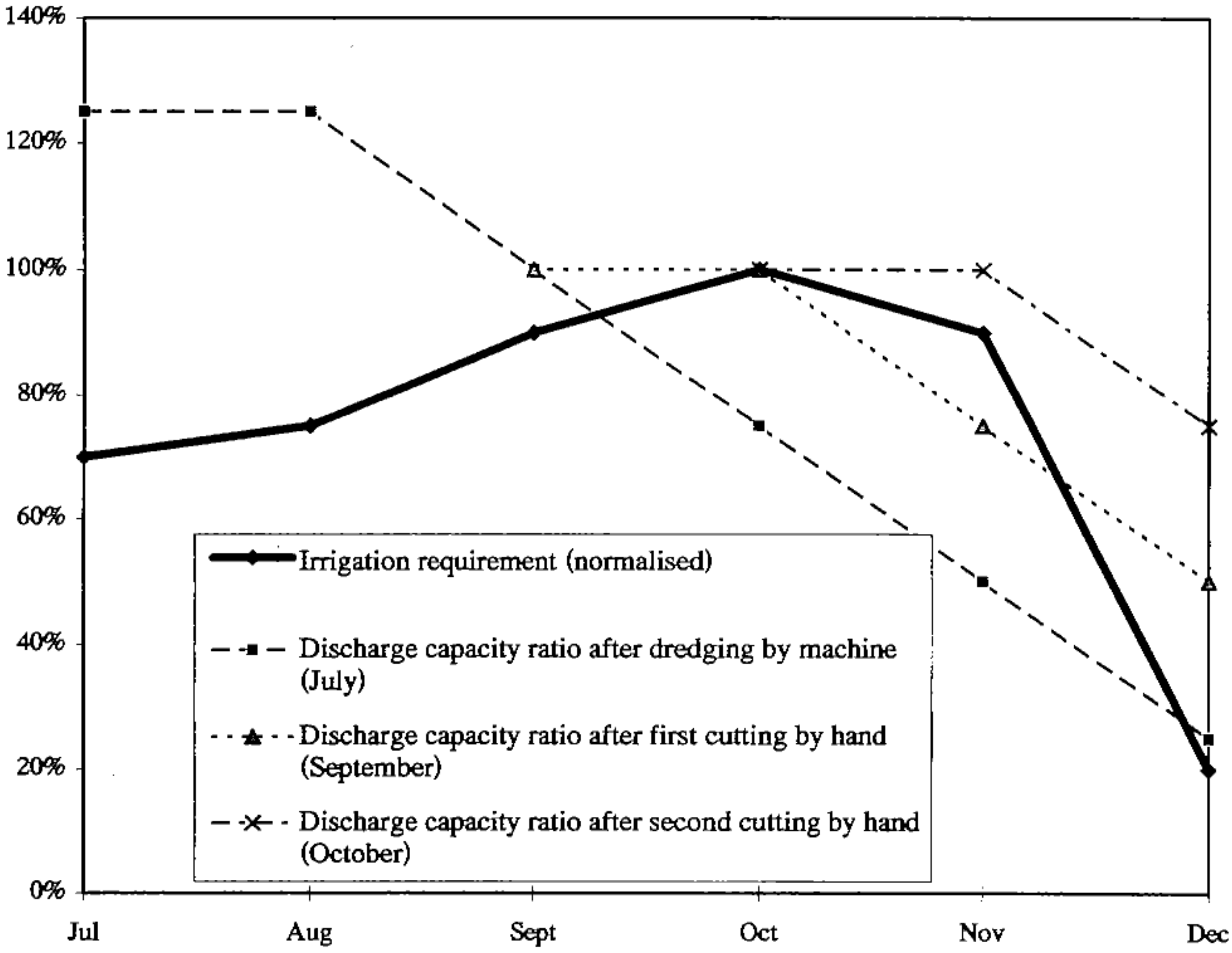


Figure 6.3 Variation in irrigation requirements and channel capacity over the season



6.2.3 Estimating the sedimentation rate and setting a desilting programme

The details of sediment rate estimation and desilting programmes are beyond the scope of this book. Sedimentation is usually slower than weed growth, so desilting operations are less frequent. These operations also have a major effect on weed growth, but generally use more resources than weed control. Therefore the desilting programme should generally be decided first, and then weed control can be scheduled to maintain the channel condition between desilting operations.

6.2.4 Identifying weed types, growth rates and feasible weed control methods

Weed types in each type of channel can be identified following Chapter 3. Data on growth rates can be collected by monitoring channel condition (e.g. monthly). Identification of feasible weed management methods was described in Chapter 4, and some of the more important considerations in developing countries are listed in Box 6.1.

Box 6.1 Criteria for selection of maintenance methods

1. Type of weeds to be controlled
- weed habit
- general control or targetted at certain species
2. Resources required
- labour
- equipment
- maintenance facilities
- fuel and spare parts
- operator skills
- herbicide
- biological agents
3. Access to channels
- service roads, on one/both banks, for foot/tracked/wheeled machine
4. Operational requirements
- draining of channel before maintenance
- time restrictions on maintenance activities
5. Environmental impacts
- water quality
- operators' health
- public health
- short/long term impacts
6. Period of effectiveness of control method
7. Estimated output/productivity of control method
8. Compatibility of control method with other maintenance activities
9. Costs
- capital/recurrent
- lifecycle/equivalent annual costs
- foreign/local currency
- finance available

6.2.5 Specifying maintenance strategy options

Once feasible control methods have been identified, a more detailed specification of each maintenance strategy can be made including methods and frequency of desilting and weed control operations on each channel type. Maintenance strategies should be programmed over extended planning periods (for example, a period of 15 years) since annual maintenance requirements are seldom constant. Planning maintenance over an extended period provides for the inclusion of more episodic components of maintenance programmes, such as desilting, which may be necessary only at three or four year intervals, and the purchase of equipment.

Specification of a maintenance programme facilitates the identification and quantification of inputs required to accomplish it. It also enables the breakdown of costs into fixed cost (capital cost) and variable cost (recurrent cost including operation and maintenance) categories and allows identification of their occurrence through time.

Once maintenance activities and inputs have been defined, the selection of the optimum maintenance strategy and programme from a list of options can be accomplished by viewing each maintenance strategy option as an investment project with expenditures occurring through time (see Chapter 7).

6.3 Programming and resource allocation for maintenance strategy options

The detailed planning and programming of a maintenance strategy option is shown in Figure 6.4.

One of the objects of producing a maintenance programme is to make effective use of the available resources (e.g. labour force, handtools, mechanical equipment, herbicides and biological agents). In most situations there will be little flexibility in the availability of resources, and the maintenance programme will therefore be resource driven rather than being demand-led. In other words, the programme must be planned around the resources availability and constraints, rather than the most convenient programme being drawn up and then the required resources procured. For example, financial constraints may preclude the purchase of hydraulic weed cutting equipment.

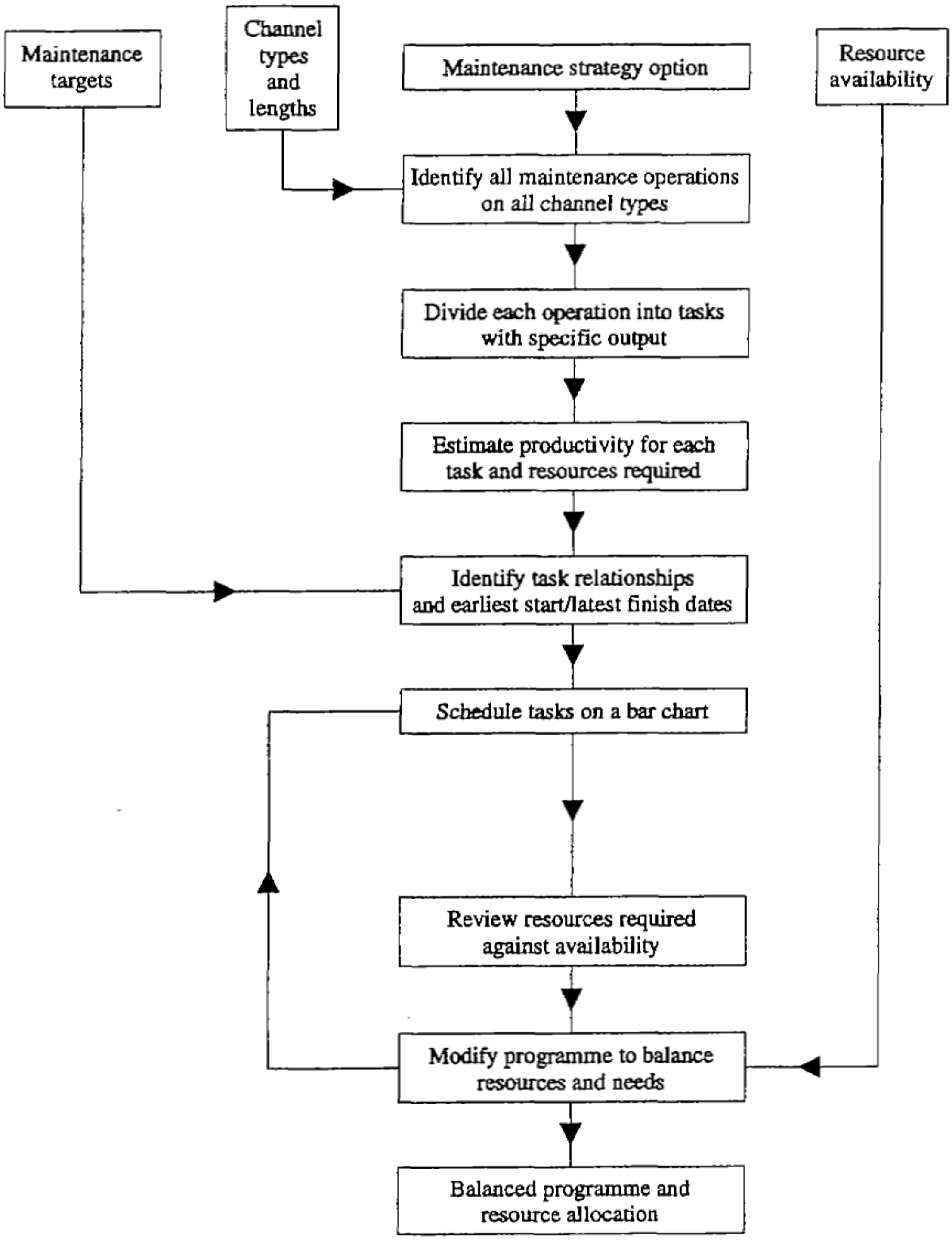
In order to obtain efficient utilisation of the scarce resources it is important that each resource is assigned to a task where it will have the greatest effect. Each irrigation or drainage channel performs a slightly different role to others, and has dimensions which may or may not be well matched to a particular maintenance method or resource (for example, the width of a channel compared to the reach of an excavator). The best maintenance method and resource will therefore vary between channels. This process provides the optimum choice of maintenance resource for each channel.

Efficient utilisation of scarce resources also requires that each resource is in use for the maximum length of time possible. This can be programmed by breaking down work into tasks, assigning the resources to the tasks, and creating a timetable for the work to be undertaken. A well planned timetable will result in maintenance work having a minimal effect on crop production and will minimise the periods of inactivity (down time) of the maintenance resources.

Note that this efficient use of resources will normally be reflected in their unit cost (by the spreading of fixed costs and reduction of surcharges at peak times). It is therefore important to consider efficient utilisation within the irrigation scheme as a whole, rather than individual channels. This may be done following the steps below which is based on work by Paul Larcher of WEDC, drawing on the Asian Development Bank (1988), Clifton (1985) and

Moder et al (1983); Microsoft Project was used in finalising the material. An example of the process is given in Section 6.4.

Figure 6.4 Preparation of balanced maintenance programme



6.3.1 Step 1: Identification of maintenance operations

The first step to take in the definition of a maintenance programme is to identify the maintenance requirements. These are intrinsically linked to the irrigation and drainage objectives for the scheme (see Chapter 5). Two issues are of particular importance in the identification of maintenance requirements:

- the total length of a particular channel or type of channel, (e.g. secondary canals) to be maintained; this should be available from the asset register;
- the timescale over which the maintenance activities must be carried out.

Time restrictions on maintenance activities impose a pressure on the available resources for weed control. In some cases they may constrain the selection of weed control strategies. For example, severe time restrictions may preclude the use of manual control because the productivity of the local labour force is insufficient to realise, in time, the desired maintenance objectives.

For each channel type, the required maintenance operations should be identified. These should include all planned maintenance activities which are necessary to maintain the hydraulic condition of the channel type over the designated planning period. These might be operations which must be carried out on an annual, or more frequent basis or they may be more episodic activities, such as desilting, that are necessary at less frequent intervals.

6.3.2 Step 2: Maintenance tasks

Each maintenance operation is broken down into its separate tasks, each with a specific output to be achieved using a specified method and major resource, for example, unskilled labour (ignoring for the present the tools and supervision needed) or excavator type XX. By dividing the maintenance operations up into individual tasks and maintaining more than one channel at a time, resource inactivity can be minimised. For example, an excavator may be dredging one channel, while the labour gang are working on another, thus preventing a labour gang standing idle while the machine is working or vice versa.

6.3.3 Step 3: Productivity and resources required

For each task derived in step 2, decide the productivity of the weed control method and estimate the major resource inputs required to complete the task under local conditions.

General estimates of the productivity of weed control methods can be obtained either from practitioners already employing the control methods or from manufacturers of equipment used for weed control. Tables 6.1 - 6.3 provide an illustration of the productivities of manual and mechanical methods of weed control. However, it should be noted that the productivity of weed control methods varies considerably according to local conditions. The factors which affect the rate at which weeds and silt may be cleared include:

- type of weed;
- rate of weed growth;
- density of weed growth;
- water levels in the channels at the time of maintenance;

- accessibility of the channels;
- quality of the maintenance work;
- skill of the labourers or operators;
- mechanism by which labourers or operators are reimbursed for their work.

Another factor to be considered at this stage is the impact a control method has on the vegetation in irrigation and drainage channels. Like productivity, this varies according to local conditions, and it also differs between control methods. Generally speaking, control methods which destroy the rooted parts of weeds as well as the aerial parts (e.g. desilting or a herbicide) are more effective than methods which eliminate only the aerial parts (e.g. cutting) (see Chapter 4).

If the impact of a control method is only of short duration, a particular channel type may require repeated treatments during the course of a year in order to meet hydraulic targets. In conjunction with any time constraints and the productivity of control methods, this factor has implications for the selection of weed control methods.

Table 6.1 Productivity of labour using different hand tools for the control of weeds in irrigation and drainage channels

Type	Use	Channel Dimensions	Productivity
Scythe [a]	Submerged, floating-leaved & emergent weeds & grass on banks	Small channels, 1 m bed width, & up to 2 m deep	15-25 m h^{-1}
Sickle, grasshook [a]	Submerged, floating-leaved & emergent weeds & grass on banks	Small channels up to 0.75-1.25 m deep	8-12 m^2 h^{-1}
Slasher	Emergent weeds & grass on banks	Up to 6 m width	500 m d^{-1}
Chain knives & chain scythes [a]	Submerged , floating-leaved & emergent weeds & grass on banks	Up to 6 m width	4-60 m^2 h^{-1} (two or three labourers)
Hoe	Submerged , floating-leaved & emergent weeds & grass on banks	Up to 6 m width	300-500 m d^{-1}
Dredging scoop	remove weeds and silt		2.8m^3

[a] Figures from Sagardoy (1982)

Table 6.2 Productivity of mechanical equipment for dredging irrigation and drainage channels.

Type	Attachment	Use	Operating Conditions	Productivity	Remarks
Dragline excavator	Small bucket ($0.3\ m^3$)	Submerged, floating-leaved & emergent weeds & silt	Operates from banks on dry or flowing channels. Reach: 9-10 m.	80 m d^{-1}[a] 120 m d^{-1}[b] 300 m d^{-1}[c]	Versatile machine adaptable to several jobs & working conditions. Spoil can be dumped clear of channel banks. Care required to avoid damage on compacted bed channels. Suitable for dredging tasks smaller than 3,000 m^{-3} km of channel.
	Large bucket ($1.0\ m^3$)	Submerged, floating-leaved & emergent weeds & silt	Operates from banks on dry or flowing channels. Reach: 18-20 m.	100 m d^{-1}[a] 160 m d^{-1}[b] 500 m d^{-1}[c]	Similar to small dragline excavator. Suitable for dredging tasks greater than 3000 m^{-3} km of channel.
Hydraulic excavator	Back-actor	Submerged, floating-leaved & emergent weeds & silt	Operates from banks on dry or flowing channels. Reach: 6-8 m; digging depth: 5-6.5 m.	800-1000 m d^{-1}[d]	Useful for dredging or weeding. Normally crawler mounted & all hydraulically operated. Those mounted on wheels require firm ground conditions. Wide variety of buckets may be fitted.
	Telescopic boom (Gradall type)	Submerged, floating-leaved & emergent weeds & silt	Reach: 9-11 m; digging depth: 6-7.5 m.	1000 $m^3\ d^{-1}$[e]	Suitable for a variety of jobs, especially excavating new channels and heavy maintenance work. Compares favourably with small draglines.
Hydraulic backhoe	Tractor-mounted	Submerged, floating-leaved & emergent weeds & silt	Reach: 5.5-6.5 m; digging depth: 3.5-4.5 m.	300-600 m d^{-1}[b]	Suitable for construction & maintenance work; also effective for excavation, dredging & weeding tasks. Most common type is the side shift which can be mounted at each side of tractor. Normally associated with front-end loader attachment. Requires good footing. More powerful & robust than trailer type.
	Trailer-mounted	Submerged, floating-leaved & emergent weeds & silt	Reach: 4.5-6.0 m; digging depth: 2.8-4.0 m.	200-400 m d^{-1}[b]	Especially suitable & economic for maintenance work. Can operate in difficult positions while prime mover remains on level standing.
Dredger		Submerged, floating-leaved & emergent weeds & silt	Maximum depth: depends on model, but for small dredgers 2 m. Spoil deposited on nearest bank or collected in special pontoons.	100-200 m d^{-1}[f]	Highly specialised machine. Cable & winch system for locomotion requires strong anchorage points along banks. Good for use in marshy ground or along channels that cannot be cleaned from banks. Difficult to transport & move in & out of channels.
Flat bed ditcher (Briscoe type)		Submerged, floating-leaved & emergent weeds & silt	Operates within dry channels, towed by tractors from each side. Bed width: 1.2-4.2 m.	3000-5000 m d^{-1}[g] 12,000 m d^{-1}[h]	More suited for construction or reconstruction of channels. Most ditchers have own engine & hydraulic unit. Requires powerful crawler tractors for towing (D6, D7). Requires experienced operator.

[a] With standard bucket and heavy excavation.
[b] With light-weight bucket and for removal of silt and vegetation.
[c] With the weed bucket but does not include cleaning of the batters.
[d] For remodelling badly silted channels.
[e] Equipped with 2.4 m wide bucket.
[f] Desilting of 1.5 m wide channel; rates for soft weeds much higher.
[g] For normal cleaning operations towed by a D6 tractor.
[h] Light cleaning operation, with wheeled tractor.
Source: Sagardoy (1982)

Table 6.3 Productivity of mechanical equipment for cutting weeds in irrigation and drainage channels.

Type	Attachment	Use	Operating Conditions	Productivity	Remarks
Dragline excavator	Weed rake	Submerged, floating-leaved & emergent weeds	Operates from banks on dry or flowing channels. Reach: 9-21 m.	500 m d^{-1}	
	Mud bucket	Submerged, floating-leaved & emergent weeds	Operates from banks on dry or flowing channels. Reach: 9-21 m.	500 m d^{-1}	
Hydraulic excavator	Oscillating grass cutter bar	Emergent weeds & grass on banks	Reach: 6-12 m; digging depth: 3-5 m.	800-1,200 m d^{-1}	Wheeled machines have reduced reach.
	Rotary cutter	Emergent weeds & grass on banks	Reach: 6-12 m; digging depth: 3-5 m.	1000m^2 h^{-1}	Wheeled machines have reduced reach.
	Flail mower	Emergent weeds & grass on banks	Reach: 6-12 m; digging depth: 3-5 m.	1000 m^2 h^{-1}	Wheeled machines have reduced reach.
	Weed cutting bucket	Submerged, floating-leaved & emergent weeds & grass on banks	Reach: 6-12 m; digging depth: 3-5 m.	600-1,000 m d^{-1}	Wheeled machines have reduced reach.
	Mud bucket	Submerged, floating-leaved & emergent weeds & grass on banks	Reach: 6-12 m; digging depth: 3-5 m	400-600 m d^{-1}	Wheeled machines have reduced reach.
Tractor	Oscillating grass cutter bar	Emergent weeds & grass on banks	Reach: 3-6 m	1000-2,500 m h^{-1}	
	Rotary cutter	Emergent weeds & grass on banks	Reach: 3-6 m	1000-2,500 m h^{-1}	
	Flail mover	Emergent weeds & grass on banks	Reach: 3-6 m	1000-2,500 m h^{-1}	
	Chain, harrow	Submerged, floating-leaved & emergent weeds	Width: 2 m	500-3,000 m h^{-1}	
Large boats (10-15hp)	Oscillating knives	Submerged, floating-leaved & emergent weeds & grass on banks	Width: 6-10 m	1000-4,000 m h^{-1} 1.5-2.8 m wide cut	
	T-shaped cutter	Submerged, floating-leaved & emergent weeds	Width: 6-10 m	1000-4,000 m h^{-1} 1.5-2.8 m wide cut	
	D-shaped cutter	Submerged, floating-leaved & emergent weeds	Width: 6-10 m	1000-4,000 m h^{-1} 1.5-2.8 m wide cut	
Small boats (4-5 hp)	Oscillating knives	Submerged, floating-leaved & emergent weeds & grass on banks	Width: 5-6 m	1000-4,000 m h^{-1} 1.0-1.8 m wide cut	

6.3.4 Step 4: Task relationships

For each task derived in step 2, decide the earliest start and latest finish dates, including the recognition of the dependency of one task or another. These dates must allow the task to be compatible with the irrigation and drainage programme and the required discharge capacity of the channel. The duration required must be realistic to allow completion of the task.

6.3.5 Step 5: Scheduling maintenance tasks on a bar chart

The maintenance operations and tasks for all the channels can be shown as bars on a large chart, also known as a Gantt chart, with the x-axis divided into convenient periods such as months or weeks. (For an example, see Figure 6.6 later in the chapter). Initially there will be some flexibility in the start and finish dates, as in step 4, and this gives flexibility in scheduling the operations and tasks to even out the demand for resources. The chart may be prepared manually, by a trial and error process, or by using a computer programme.

It may be helpful to prepare a network diagram first, to show the relationships between the tasks, e.g., the order in which the tasks must be undertaken and tasks that may run consecutively.

6.3.6 Step 6: Reviewing the total resource requirements against availability

Resources should be allocated to each task in the diagram according to the requirements given in step 3. The allocation of resources will depend on the time available to complete the task and the resource used (see step 7 below). The start and finish dates can then be fixed for each task and the total resource requirements for each time period (e.g. month) are calculated and compared against those available.

6.3.7 Step 7: Modifying the programme to balance resources and needs

Unfortunately the first attempt to achieve a programme usually results in unacceptable or unavailable peaks in resource demand during certain times of the year and under utilisation of resources during others. In this case, the scheduling process should modified until a satisfactory result is obtained.

The alterations which may be made are:

a.) Extending the task start and finish dates, so long as this will have an acceptable or minimal effect on the crop production.

b.) Changing the resource allocated to the task for either a faster resource, if time constraints are a problem, or a resource in lower demand if peak demand is a problem. Changing the allocated resource may require a reappraisal of control methods or the resources in order to determine the most appropriate task for resource reallocation.

If a particular resource is available but not fully utilised following the balancing process, e.g. one excavator regularly idle, a global review of the maintenance programme may be carried out to determine if the overall preferred option would be to keep the resource idle or use it in another task, where it may not be the most suitable.

6.3.8 Step 8: Completion of the balanced programme and resource allocation

The result of working through steps 1 to 7 is the production of a balanced programme for the maintenance strategy option. This then needs to be compared with the programmes from other feasible strategy options, as described in Chapters 7 and 8. Following the selection of a maintenance programme, the approved programme Gantt or bar chart is then used to prepare work schedules for the different resources and their supervisors.

The maintenance manager should review the timetable at frequent intervals to check targets are being met and make alterations to the resources to allow for unexpected delays or emergency work. These reviews require a repetition of steps 3 to 6.

Box 6.2 Resource review

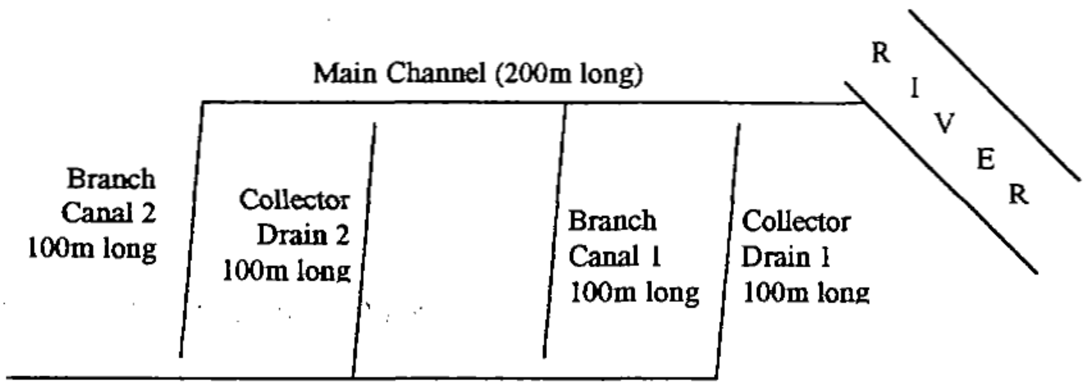
In order to choose the best resource for each task, its suitability should be assessed against four factors:

1. **Availability** Resource availability is the most important factor when choosing the maintenance method and should therefore be considered first and then reconsidered with the other three parameters before the final method is chosen. The availability of a particular resource may have seasonal variations (e.g. the strength of the labour force may be reduced during crop harvest). Support services must also be available; a mechanical excavator will be useless if fuel and maintenance facilities can not be obtained locally. Skilled workers would also be needed to apply herbicide, implement biological control, operate machinery and train others in the appropriate techniques.
2. **Cost** The costs of each method and resource are assessed and compared with each other. There may also be seasonal variations in the costs of some resources e.g. labour wages. The resource which is cheapest per unit of output will generally be the most desirable.
3. **Time** The time taken to complete the task depending on the method and resource used needs to be considered, e.g. the time taken to drain, maintain and refill a channel may be unacceptable. Some methods will be significantly faster than others, however, the time period between each maintenance session also needs to be considered.
4. **Quality** The quality of the work carried out by each resource should be assessed in order to decide if the use of the resource will be acceptable. This may be measured as the condition of the channel after maintenance and the regrowth rate.

6.4 Maintenance programming example

The maintenance programming technique may be demonstrated by the following simplified example. Consider an irrigation system consisting of a main channel with 2 branch canals and 2 collector drains outfalling to a main drain as shown in Figure 6.5. The maintenance timetable will be built up for one year.

Figure 6.5 Maintenance programming example- irrigation and drainage system



Step 1. Maintenance Operation

The maintenance operations during the year are identified for each channel (Table 6.4).

Table 6.4 Maintenance programming example - operations over a 12 month period

Main canal	Branch canal	Collector drain	Main drain
desilt	desilt	remove weeds (1)	desilt
remove weeds	remove weeds (1)	desilt (if required)	remove weeds (1)
-	remove weeds (2)	remove weeds (2)	remove weeds (2)
-	-	-	remove weeds (3)

Note: (1) indicates operation undertaken for the first time

(2) indicates operation undertaken for the second time etc.

Step 2. Maintenance tasks

For each channel the maintenance operations are broken down into their individual tasks.

Main channel: Broken down into 100 m task sections, with the top end maintained first to prevent silt and weeds from maintenance work being washed into a maintained section.

Branch Channels: Broken down into 50 m task sections, with the top end maintained first to prevent silt and weeds from maintenance work being washed into a maintained section.

Collector drains: Drains are broken down into 50 m task sections. Dredging is only occasionally required, but should be shown to indicate that resources may be required. The maintenance requirements of both collector drains are the same in this example.

Main Drain: The main drain is broken down into 100 m task sections.

Step 3: Productivity and resources required

For this example it will be assumed that there is one excavator and one labour gang available. The allocation of resources for a more complex problem would require the use of resource optimisation as described above.

The resources required for each task are identified, from which task data are specified. This includes the duration of the task and the resources to be used, as shown in the first four columns of Table 6.5.

Step 4: Task timing constraints and relationships

Where a task cannot be started until another has been finished (e.g., the task on an upstream section of channel) the link with the predecessor task is identified.

In addition, constraints on the start or finish dates are assigned to tasks as appropriate in order to be compatible with water demand and crop production. A "start no earlier than" constraint marks the earliest a task can start, and a "finish no later than" constraint fixes the latest a task can finish.

The right hand columns of Table 6.5 shows both timing constraints and any predecessor tasks, for each task. These data represent the requirements which have to be met by the maintenance programme.

Step 5: Scheduling maintenance tasks on a bar chart

The maintenance programme is shown as a bar chart in Figure 6.6. This is based on the resource requirements, constraints and predecessor links given in Table 6.5.

Step 6: Reviewing the total resource requirements against availability

After preparing the programme chart (Figure 6.6), it is necessary to check the utilisation of resources, to ensure that there are no periods when the amount of each resource scheduled for use exceeds that available. The result for this example is shown in Table 6.6. If there is a problem of excess allocation, the programme must then be adjusted to achieve an acceptable balance of resources. In some cases it may be impossible to meet all the constraints, and some may need to be relaxed, for example, operations allowed to finish late or scheduled in a different order, or additional resources used (perhaps at greater expense).

Table 6.5 Maintenance programming example

Task Number	Task Name	Resource	Duration (weeks)	Constraint	Constraint Date	Predecessor tasks
1	Desilt Main Canal		6	As Soon As Possible		
2	desilt MC 0-100m	excavator	3	Start No Earlier Than	01/01/96	
3	desilt MC 100-200m	excavator	3	Finish No Later Than	28/02/96	2
4	Weed Main Canal		4	As Soon As Possible		
5	weed MC 0-100m	labour gang	2	Start No Earlier Than	01/06/96	
6	weed MC 100-200m	labour gang	2	Finish No Later Than	30/09/96	5
7	Desilt Branch Canal 1		2	As Soon As Possible		
8	desilt BC1 0-50m	excavator	1	As Soon As Possible		2
9	desilt BC1 50-100m	excavator	1	Finish No Later Than	28/03/96	8
10	Weed (1) Branch Canal 1		2	As Soon As Possible		
11	weed (1) BC1 0-50m	labour gang	1	As Soon As Possible		5
12	weed (1) BC1 50-100m	labour gang	1	Finish No Later Than	31/07/96	11
13	Weed (2) Branch Canal 1		2	As Soon As Possible		
14	weed (2) BC1 0-50m	labour gang	1	Start No Earlier Than	01/09/96	
15	weed (2) BC1 50-100m	labour gang	1	Finish No Later Than	30/10/96	14
16	Desilt Branch Canal 2		2	As Soon As Possible		
17	desilt BC2 0-50m	excavator	1	As Soon As Possible		3
18	desilt BC2 50-100m	excavator	1	Finish No Later Than	30/04/96	17
19	Weed (1) Branch Canal 2		2	As Soon As Possible		
20	weed (1) BC2 0-50m	labour gang	1	As Soon As Possible		6
21	weed (1) BC2 50-100m	labour gang	1	Finish No Later Than	31/07/96	20
22	Weed (2) Branch Canal 2		2	As Soon As Possible		
23	weed (2) BC2 0-50m	labour gang	1	Start No Earlier Than	01/09/96	
24	weed (2) BC2 50-100m	labour gang	1	Finish No Later Than	31/10/96	23
25	Clear (1) Collector Drain 1		4	As Soon As Possible		
26	weed (1) CD1 100-50m	labour gang	1	Start No Earlier Than	01/04/96	
27	desilt CD1 100-50m	excavator	1	As Soon As Possible		26
28	weed (1) CD1 50-0m	labour gang	1	As Soon As Possible		27

29	desilt CD1 50-0m	excavator	1	Finish No Later Than	31/12/96	28
30	Weed (2) Collector Drain 1		2	As Soon As Possible		
31	weed (2) CD1 100-50m	labour gang	1	Start No Earlier Than	01/11/96	
32	weed (2) CD1 50-0m	labour gang	1	Finish No Later Than	31/12/96	31
33	Clear (1) Collector Drain 2		4	As Soon As Possible		
34	weed (1) CD2 100-50m	labour gang	1	Start No Earlier Than	01/04/96	
35	desilt CD2 100-50m	excavator	1	As Soon As Possible		34
36	weed (1) CD2 50-0m	labour gang	1	As Soon As Possible		35
37	desilt CD2 50-0m	excavator	1	As Soon As Possible		36
38	Weed (2) Collector Drain 2		2	As Soon As Possible		
39	weed (2) CD2 100-50m	labour gang	1	Start No Earlier Than	01/11/96	
40	weed (2) CD2 50-0m	labour gang	1	Finish No Later Than	31/12/96	39
41	Desilt Main Drain		6	As Soon As Possible		
42	desilt MD 200-100m	excavator	3	As Soon As Possible		37
43	desilt MD 100-0m	excavator	3	As Soon As Possible		42
44	Weed (1) Main Drain		4	As Soon As Possible		
45	weed (1) MD 200-100m	labour gang	2	Start No Earlier Than	01/03/96	
46	weed (1) MD 100-0m	labour gang	2	As Soon As Possible		45
47	Weed (2) Main Drain		4	As Soon As Possible		
48	weed (2) MD 200-100m	labour gang	2	Start No Earlier Than	01/08/96	
49	weed (2) MD 100-0m	labour gang	2	As Soon As Possible		48
50	Weed (3) Main Drain		4	As Soon As Possible		
51	weed (3) MD 200-100m	labour gang	2	Start No Earlier Than	01/10/96	
52	weed (3) MD 100-0m	labour gang	2	As Soon As Possible		51

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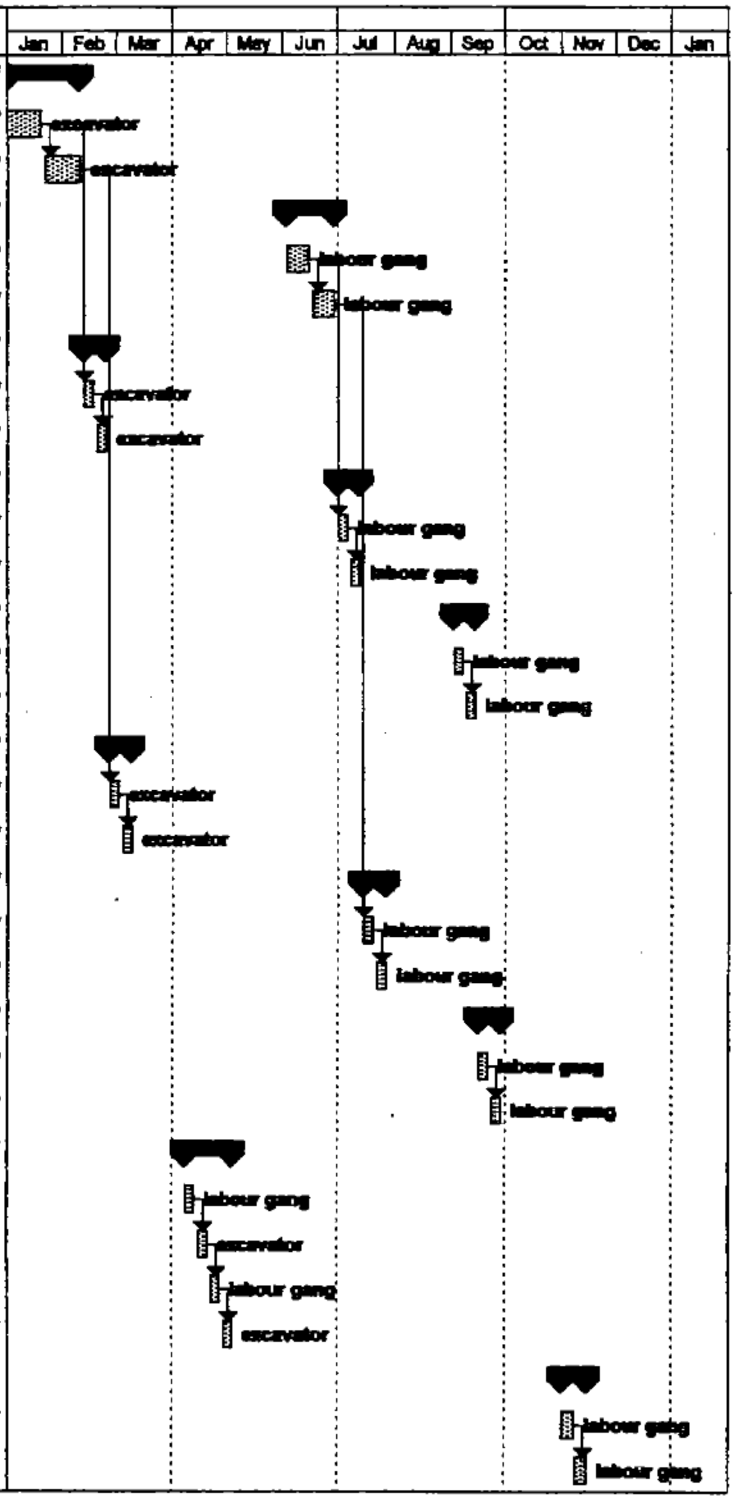
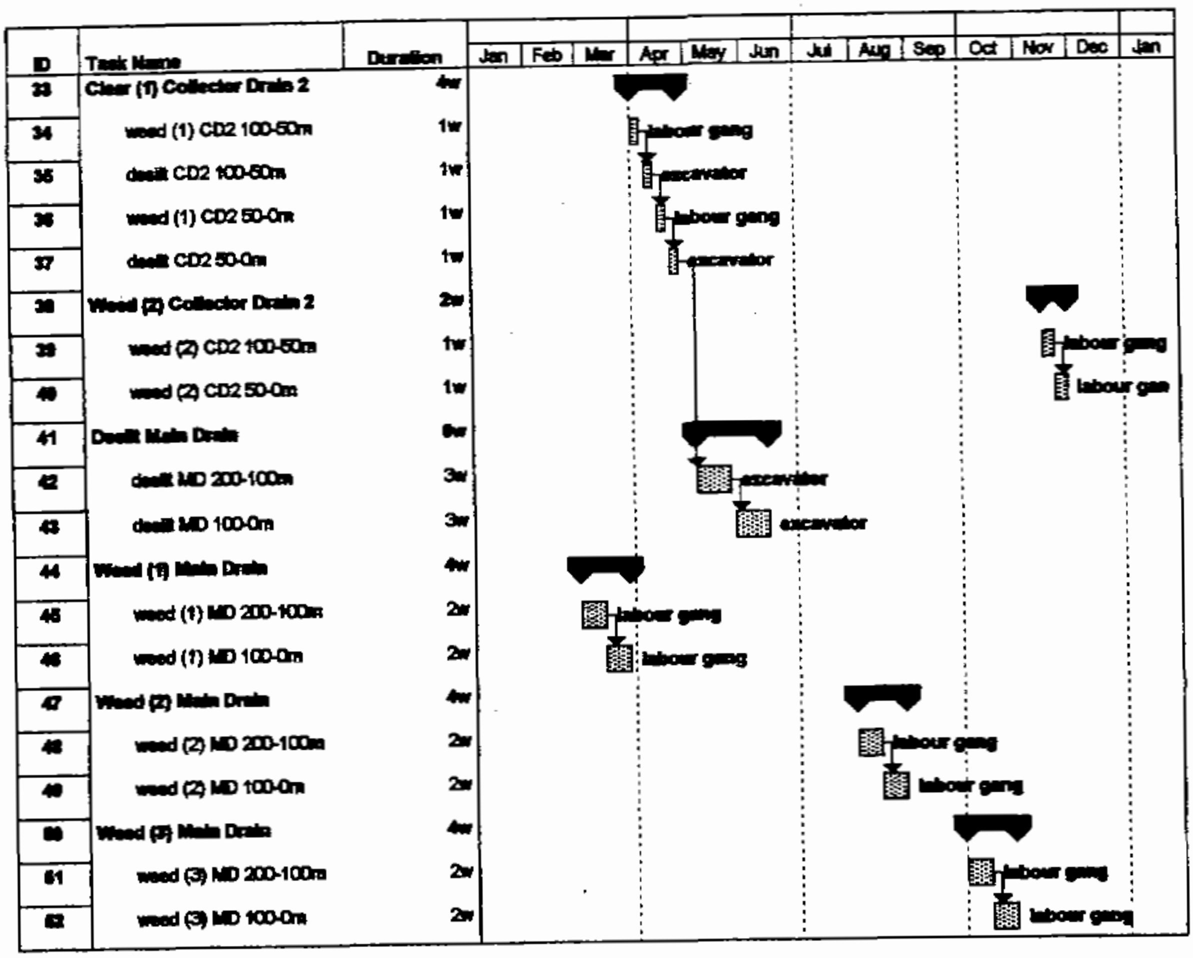
Moder J, Phillips C, and Davis E, (1983), Project management with CPM, PERT and precedence diagramming, Van Nostrand Reinhold, UK

Figure 6.6 Maintenance programming example - resource usage table

ID	Task Name	Duration
1		6w
2	desilt MC 0-100m	3w
3	desilt MC 100-200m	3w
4	Weed Main Canal	4w
5	weed MC 0-100m	2w
6	weed MC 100-200m	2w
7	Desilt Branch Canal 1	2w
8	desilt BC1 0-50m	1w
9	desilt BC1 50-100m	1w
10	Weed (1) Branch Canal 1	2w
11	weed (1) BC1 0-50m	1w
12	weed (1) BC1 50-100m	1w
13	Weed (2) Branch Canal 1	2w
14	weed (2) BC1 0-50m	1w
15	weed (2) BC1 50-100m	1w
16	Desilt Branch Canal 2	2w
17	desilt BC2 0-50m	1w
18	desilt BC2 50-100m	1w
19	Weed (1) Branch Canal 2	2w
20	weed (1) BC2 0-50m	1w
21	weed (1) BC2 50-100m	1w
22	Weed (2) Branch Canal 2	2w
23	weed (2) BC2 0-50m	1w
24	weed (2) BC2 50-100m	1w
25	Clear (1) Collector Drain 1	4w
26	weed (1) CD1 100-50m	1w
27	desilt CD1 100-50m	1w
28	weed (1) CD1 50-0m	1w
29	desilt CD1 50-0m	1w
30	Weed (2) Collector Drain 1	2w
31	weed (2) CD1 100-50m	1w
32	weed (2) CD1 50-0m	1w




ID
Task Name
Duration
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
33 Clear (1) Collector Drain 2 4w
34 weed (1) CD2 100-50m 1w
35 desilt CD2 100-50m 1w
36 weed (1) CD2 50-0m 1w
37 desilt CD2 50-0m 1w
38 Weed (2) Collector Drain 2 2w
39 weed (2) CD2 100-50m 1w
40 weed (2) CD2 50-0m 1w
41 Desilt Main Drain 6w
42 desilt MD 200-100m 3w
43 desilt MD 100-0m 3w
44 Weed (1) Main Drain 4w
45 weed (1) MD 200-100m 2w
46 weed (1) MD 100-0m 2w
47 Weed (2) Main Drain 4w
48 weed (2) MD 200-100m 2w
49 weed (2) MD 100-0m 2w
50 Weed (3) Main Drain 4w
51 weed (3) MD 200-100m 2w
52 weed (3) MD 100-0m 2w
labour gang
excavator
labour gang
excavator
labour gang
labour gan
excavator
excavator
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labour gang
labour gang

CHAPTER 7

ESTIMATING THE COSTS OF A MAINTENANCE PROGRAMME

7.1 Introduction

In Chapter 6 we considered how to prepare maintenance strategy options and programmes to achieve the target level of service and the efficient physical utilisation of major resources. This process will normally result in several balanced programme options, one corresponding to each strategy option, as shown in Figure 6.1.

The final selection of the maintenance strategy will depend on a cost criterion: minimisation of the life cycle cost over the planning period. In this chapter we consider how to estimate this life cycle cost, and the setting of maintenance budgets, as already outlined in Figure 6.1.

The chapter is divided into the following sections:

- identification of inputs and input costs for each task
- estimation of annual costs for a particular programme over the extended planning period
- calculation of the present value of the costs, and hence the annualised costs, over the extended planning period.

In Chapter 8 we then use this approach to compare the costs of different maintenance strategy options.

7.2 Identification of the inputs and estimation of input cost for each task

There are several steps to be taken in determining the inputs required to fulfil a maintenance programme:

- identification of the maintenance requirements (Chapter 5);
- quantification of the productivity of selected control methods (Chapter 6);
- specification of the maintenance programme (Chapter 6);
- scheduling the inputs required to fulfil the specified maintenance programme (Chapter 6).

The information generated at each stage of the process ultimately enables the calculation of the costs associated with the specified maintenance programme. In defining the costs, annual input requirements should be calculated over an extended planning period.

Following the specification of a maintenance programme, it is necessary to determine the inputs required to fulfil the programme. These will vary according to the nature of the control methods adopted in the programme. For example, at the simplest level, labour and hand-tools might be the only inputs required to maintain a channel (or hierarchy of channels). Conversely, if the use of mechanical equipment is a component of a maintenance programme, then the list of inputs will be more extensive and will include all items relating to operation and maintenance of the machinery (e.g. fuel and repairs). In the case of mechanical equipment, manufacturers often produce handbooks giving guidance on the estimation of operating costs of equipment, including figures for the rates of fuel and lubricant consumption. Alternatively, hourly or daily charge rates could be used if available (e.g. hire rates, or charge rates set by the irrigation agency or a government department). These simplify the calculations, but we have taken a more fundamental approach here, to show cash flow in the common situation where equipment has to be purchased.

Initially, input requirements should be determined on a unit basis (e.g. per kilometre of secondary canal) and then total input requirements for a specified programme can be calculated at a later stage. Allied to the identification of inputs is the quantification of input costs. Likewise, these should be expressed as unit costs. Tables 7.1 to 7.3 detail the information required on inputs associated with different methods of weed control.

Table 7.1 Information required on inputs for different methods of weed control.

Information Required		**Method of Control**				
Input	**Unit Cost/Measure**	**Manual**		**Chemical**		
	(Costs in local currency)	Hand-held tools	Boom	Knapsack sprayer	Weed wipe	Boat
Capital cost of equipment & materials						
Hand tool	Cost per tool	✓				
Knapsack sprayer	Cost per sprayer			✓		
Weed wipe	Cost per wipe				✓	
Boat[(a)]	Cost per boat					✓
Herbicide	Cost per litre			✓	✓	✓
Protective clothing	Cost per outfit per labourer	✓		✓	✓	✓
Boom	Cost per metre		✓			
Application rate/use						
Herbicide	Litres per hectare			✓	✓	
Machine utilisation	Annual operating hours per machine					✓
Insurance						
Cost	Annual cost per machine					✓
Road tax						
Cost	Annual cost per machine					
Fuel						
Consumption	Litres per hour					✓
Cost	Cost per litre					✓
Lubricants						
Consumption	Litres per hour					✓
Cost	Cost per litre					✓
Filter allowance	Percentage of hourly lubricant cost					✓
Repair costs						
Labour	Cost per hour	✓	✓	✓	✓	✓

Parts/materials						
Hand-tool		✓				
Knapsack sprayer				✓		
Weed wipe					✓	
Boat[a]						✓
Boom			✓			
Life of equipment/materials						
Hand tool	Years	✓				
Knapsack sprayer	Years			✓		
Weed wipe	Years				✓	
Boat[a]	Years					✓
Protective clothing	Years	✓		✓	✓	✓
Boom	Years					✓
Labour rates						
Labourer	Cost per hour	✓	✓			
Knapsack sprayer	Cost per hour			✓	✓	
Machine operator	Cost per hour					✓
Mechanic	Cost per hour					✓
Watchman	Cost per hour					✓
Allowance for overheads	(See text)	✓		✓	✓	✓
Productivity of control method	Metres per hour	✓	✓	✓	✓	✓
Frequency of treatment	Number of treatments per year	✓	✓	✓	✓	✓

[a] Inclusive of tanks, spray booms, etc.

Table 7.2 Information required on inputs for mechanical weed control.

Information Required		Mechanical Control					
Item	**Measure**	**Cutting/Harvesting**			**Dredging**		
	(Costs in local currency)	Hydraulic Excavator	Tractor	Boat	Hydraulic Excavator	Tractor	Boat
Capital cost of equipment							
Excavator	Cost per machine	✓			✓		
Tractor	Cost per machine		✓			✓	
Boat[a]	Cost per machine			✓			✓
Grenadier	Cost per machine		✓			✓	
Mowing bucket	Cost per bucket	✓	✓				
Dredging bucket	Cost per bucket				✓°	✓	
Machine utilisation	Annual operating hours per machine	✓	✓	✓	✓	✓	✓
Insurance cost							
Excavator	Annual cost per machine	✓			✓		
Tractor	Annual cost per machine		✓			✓	
Boat	Annual cost per machine			✓			✓
Grenadier	Annual cost per machine		✓			✓	
Mowing bucket	Annual cost per bucket	✓	✓				
Dredging bucket	Annual cost per bucket				✓	✓	

Road tax cost							
Excavator	Annual cost per machine	✓			✓		
Tractor	Annual cost per machine		✓			✓	
Fuel							
Consumption							
Excavator	Litres per hour	✓			✓		
Tractor	Litres per hour		✓			✓	
Boat	Litres per hour			✓			✓
Cost	Cost per litre	✓	✓	✓	✓	✓	✓
Lubricants							
Consumption							
Excavator	Litres per hour	✓			✓		
Tractor	Litres per hour		✓			✓	
Boat[(a)]	Litres per hour			✓			✓
Grenadier	Litres per hour		✓			✓	
Mowing bucket	Litres per hour	✓	✓				
Cost	Cost per litre	✓	✓	✓	✓	✓	✓
Filter allowance	Percentage of hourly lubricant cost	✓	✓	✓	✓	✓	✓
Tyre costs	Cost per tyre	✓[(b)]	✓		✓[(b)]	✓	
Repair costs							
Labour	Cost per hour	✓	✓	✓	✓	✓	✓
Parts/materials							
Excavator		✓			✓		
Tractor			✓			✓	
Boat[(a)]				✓			✓
Grenadier			✓			✓	
Mowing bucket		✓	✓				
Dredging bucket					✓	✓	
Life of equipment							
Excavator	Years	✓			✓		
Tractor	Years		✓			✓	
Boat[(a)]	Years			✓			✓
Grenadier	Years		✓			✓	
Mowing bucket	Years	✓	✓				
Dredging bucket	Years				✓	✓	
Tyres	Years	✓[(b)]			✓[(b)]		
Labour rates							
Machine operator	Cost per hour	✓	✓	✓	✓	✓	✓
Mechanic	Cost per hour	✓	✓	✓	✓	✓	✓
Watchman	Cost per hour	✓		✓	✓		✓
Allowance for overheads	(See text)	✓	✓	✓	✓	✓	✓
Productivity of control method	Metres per hour	✓	✓	✓	✓	✓	✓
Frequency of treatment	Number of treatments per year	✓	✓	✓	✓	✓	✓

[a] Inclusive of hydraulic arms and cutting blades or dredging buckets, etc.

[b] Wheeled excavators only.

[c] If not supplied with excavator.

Table 7.3 Information required on inputs for environmental/biological weed control.

Information Required		**Method of Control**					
Item	**Measure**	**Environmental**			**Biological**		
	(Costs in local currency)	Shading	Burning	Water levels	Competitive plants	Herbivorous fish	Herbivorous insects
Capital cost of materials/biological agents							
Hand-tools	Cost per tool	✓	✓		✓	✓	
Shading plants/materials	Cost per plant/metre	✓					
Competitive plants	Cost per plant				✓		
Herbivorous fish	??					✓	
Herbivorous insects	??						✓
Containment structures	Total capital cost					✓	
Additional costs							
Licence	Annual cost		✓			✓	✓
Stocking rates/application rate	Number of biological agents per metre	✓			✓	✓	✓
Maintenance/repair costs							
Labour	Cost per hour	✓			✓	✓	
Parts/materials							
Shading materials		✓					
Containment structures						✓	
Life of materials/biological agents							
Hand-tools	Years	✓	✓		✓	✓	
Shading plants/materials	Years	✓					
Competitive plants	Years				✓		
Herbivorous fish	Years					✓	
Herbivorous insects	Years						✓
Containment structures	Years					✓	
Labour rates							
Labourer	Cost per hour	✓	✓	✓	✓	✓	
Consultant	Cost per hour					✓	✓
Watchman	Cost per hour					✓	
Specialist staff	Cost per hour					✓	✓
Allowance for overheads	(See text)					✓	✓
Productivity of control method	(See text)	✓	✓		✓		
Frequency of treatment	(See text)	✓	✓	✓	✓	✓	✓

7.3 Estimation of the input costs associated with the specified maintenance programme

The total costs associated with specified maintenance programmes can be calculated once the information detailed in Section 7.2 has been obtained. The process is illustrated by an example drawn from our experience at Mwea Irrigation Settlement Scheme, Kenya (Mwea ISS, as described in Chapter 2).

7.3.1 Identification of the maintenance operations

Based on the climatic, agricultural and labour constraints at Mwea ISS, the maintenance programme includes dredging of primary and secondary canals (90 km total length) every year between January and March. In addition, to meet irrigation objectives, the entire length of these channels is manually cut on two occasions, in June and September.

Thus, the maintenance operations are as follows:

- to dredge 90,000 m of primary and secondary channels in three months;
- to manually cut 90,000 m of primary and secondary canals in June and September.

7.3.2 Estimation of the productivity of selected control methods

The estimated average output for mechanically dredging primary and secondary canals at Mwea ISS is 50 m of channel per hour[1].

The estimated average output for manually cutting primary and secondary canals at Mwea ISS is 50 m of channel per labourer per day.

7.3.3 Unit costs of the inputs required to fulfil the maintenance operations

The inputs required to fulfil the maintenance tasks on primary and secondary canals are classified in Table 7.4. The unit costs associated with the inputs are also quantified in the table, expressed in constant prices (local currency in 1994).

For each of the maintenance tasks specified (mechanical dredging and manual cutting), there are associated fixed costs and recurrent costs. The fixed costs are the capital costs of machines (hydraulic excavators) or equipment (i.e. the tools) whilst the recurrent costs are those costs incurred in operating and maintaining the machines or equipment (e.g. labour, fuel and parts). For simplicity here the recurrent costs are assumed constant from year to year, at the average levels as recommended by the manufacturer.[2]

[1]This figure is based on average productivities of a Komatsu PC200-5 hydraulic excavator with a 0.7 m^3 bucket and a Komatsu PC100-3 hydraulic excavator with a 0.4 m^3 bucket, both operating over a range of conditions.

[2]In practice there will be an increase in repair costs as equipment nears the end of its life

Table 7.4 Classification of the inputs required to fulfil maintenance operation on primary and secondary canals at Mwea ISS.

Maintenance operation	Inputs	Input cost per unit (KSh)	
Mechanical dredging	Hydraulic excavator	9,000,000.00	per machine [a]
	Insurance	752.63	per year [b]
	Road tax	1,500.00	per year [b]
	Fuel	21.90	per litre [b]
	Lubricants, grease, filters		
	Engine oil	76.18	per litre [b]
	Transmission or swing machinery oil	76.18	per litre [b]
	Final drive oil	76.18	per litre [b]
	Hydraulic oil	93.40	per litre [b]
	Grease	86.95	per kilogram [b]
	Filter allowance (50 % total hourly lubricant cost)	10.56	per hour [c]
	Repairs		
	Parts	92.90	per hour [d]
	Labour	17.75	per hour [d e]
	Operator	14,556.00	per year [f]
	Watchman	12,036.00	per year [f]
Manual cutting	Hand-tools	120.00	per tool [b]
	Labourer	33.42	per day [f]

[a] unit cost, based on Komatsu PC200-5 supplied by Panafrican Equipment, Nairobi, October 1994.
[b] unit costs supplied by National Irrigation Board, Mwea, 1994.
[c] filter allowance recommended by Komatsu (1994).
[d] hourly requirements for parts and labour recommended by Komatsu (1994).
[e] unit cost of labour supplied by National Irrigation Board, Mwea, 1994.
[f] unit costs based on Casual Workers Salary Amendment and Agricultural Industry Order Number: 1994 Legal Notice Number 162, supplied by National Irrigation Board, Mwea, 1994.

In most instances it is appropriate to combine all the recurrent cost items associated with a machine and express recurrent costs as a single figure. Table 7.5 illustrates the calculation of annual recurrent costs for a hydraulic excavator. In this case, the machine utilisation is assumed to be 1,500 hours per year.

Table 7.5 Annual recurrent costs for a Komatsu PC200-5 hydraulic excavator.

Input	Unit cost (KSh)	Number of units required	Annual sub-total (KSh)
Insurance	752.63	1	752.63
Road tax	1,500.00	1	1,500.00
Fuel[a]	21.90	12.5 l h^{-1}; 1500 h y^{-1}	410,625.00
Lubricants, grease, filters			
Engine oil[a]	76.18	0.076 l h^{-1}; 1500 h y^{-1}	8,685.00
Transmission or swing machinery oil[a]	76.18	0.009 l h^{-1}; 1500 h y^{-1}	1,035.00
Final drive oil[a]	76.18	0.008 l h^{-1}; 1500 h y^{-1}	915.00
Hydraulic oil[a]	93.40	0.085 l h^{-1}; 1500 h y^{-1}	11,910.00
Grease[a]	86.95	0.07 kg h^{-1}; 1500 h y^{-1}	9,135.00
Filter allowance (50% total hourly lubricant cost)[b]	10.56	1 unit/hr; 1500 h y^{-1}	15,840.00
Repairs			
Parts	92.90	1 unit/hr; 1500 h y^{-1}	139,350.00
Labour	17.75	1 unit/hr; 1500 h y^{-1}	26,625.00
Operator's annual wage	14,556.00	1	14,556.00
Watchman's annual wage	12,036.00	5	60,180.00
Total annual recurrent cost			**701,108.63**

[a] rates for hourly consumption supplied by Komatsu (1994).
[b] filter allowance recommended by Komatsu (1994).

7.3.4 Estimation of the resources required and input costs associated with the specified maintenance programme

The resources required in this example are hydraulic excavators, handtools and labour. It is necessary to consider the number of each required for the maintenance programme, and estimate their capital and recurrent costs. The procedures are illustrated in Sections 7.3.4.1 to 7.3.4.3[3]. In addition, provision must be made for overheads. These include the costs of management and supervision, payments, office and workshop facilities, and any surplus which the operation is required to make (e.g. to contribute to central overheads). Provision for overheads is usually made by adding a percentage (e.g. 20%) to the calculated input costs.

[3] ideally these sections would be formatted as boxes

7.3.4.1 Hydraulic excavators - number required and costs

7.3.4.1.1 Unit cost of excavator

In the present example, the capital cost of the hydraulic excavator, including import duties, is taken to be KSh.9,000,000 (Panafrican Equipment, Nairobi 1994). The annual number of operating hours for such a machine is assumed to be 1,500 and the working life of the machine is assumed to be 10,500 hours. Thus, for this maintenance programme, capital investment in hydraulic machinery is required every seven years.

7.3.4.1.2 Number of excavator units required

The total number of excavators required in order to fulfil the desilting activity in the specified time is a function of the productivity of the machine and the number of machine operating hours. The total number of excavators required can be calculated as follows:

Operation	To mechanically dredge 90,000m of main and branch canals within a period of 3 months
Average output for mechanical dredging (National Irrigation Board, Mwea, 1994)	50m length of main or branch canal per hour.
Number of excavator hours required to mechanically dredge 90,000m of main and branch canals	$\frac{90,000}{50}$ = 1800 hours
Standard number of operating hours for one excavator in a three month period, based on a 6 hour working day and 26 working days per month (National Irrigation Board, Mwea, 1994)	6 x 26 x 3 = 468 hours
Average rate of excavator utilisation	*c.* 80 %
Average number of operating hours for one hydraulic excavator in a three month period (Note that this is equivalent to 1,500 hours per year)	468 x 80 % = 374 hours
Total number of excavators required to mechanically dredge 90,000 m of main and branch canals within a three month period each year	$\frac{1,800}{374}$ = 4.8 = 5 excavators

7.3.4.1.3 Input cost of excavators for this maintenance programme

Although a total of five hydraulic excavators is required in order to dredge primary and secondary canals at Mwea ISS, the excavators are only required for three months each year. The 80% utilisation rate includes an allowance for the time required for servicing and repairs. For the remaining nine months the excavators are assumed to be used elsewhere, for example, on other maintenance or construction work. This is an important assumption, which has a major impact on the costs and therefore must be treated with care. On many irrigation schemes hydraulic equipment will be idle for at least part of the year, so the share of capital cost attributable to maintenance will be greater than the part of the year during which it is used. (For an example of this, see Section 7.3.4.2 on handtools where the whole cost is assigned to the maintenance programme.) In calculating the capital input cost of hydraulic excavators for desilting primary and secondary canals in our example we apportion only one quarter of the total capital cost. Thus, the capital input cost of the hydraulic excavators is calculated as follows:

Capital cost of five PC200-5 hydraulic excavators	KSh.9,000,000 x 5 = KSh.45,000,000
Number of months excavators employed dredging main and branch canals in Year 1	3 months
Capital cost attributable to main and branch canals	KSh.45,000,000 x $\frac{3}{12}$ = KSh.11,250,000

Therefore a capital cost of KSh.11,250,000 will be incurred by the maintenance programme in each of Years 1, 8, 15 etc.

7.3.4.1.4 Hydraulic excavators - annual recurrent costs

In this example, the recurrent input costs associated with a single hydraulic excavator were calculated to be KSh.701,108.63 per year at 1994 prices (see Table 7.5).

In accordance with the premise that only one-quarter of the capital cost of the hydraulic excavators should be assigned to the desilting of primary and secondary canals, it is appropriate to allot the same proportion of the annual recurrent costs of the hydraulic excavators to the maintenance activity. This can be calculated as follows:

Annual recurrent costs of five hydraulic excavators	KSh.701,108.63 x 5 = KSh.3,505,543.15
Number of months excavators employed dredging main and branch canals	3 months
Annual recurrent costs attributable to main and branch canals	KSh.3,505,543.10 x $\frac{3}{12}$ = KSh.876,385.79

Therefore recurrent cost of KSh.876,385.79 will be incurred by the maintenance programme each year.

7.3.4.2 Hand-tools (panga) - number required and capital cost

7.3.4.2.1 Unit cost of hand-tool

In the present example, the capital cost of each hand-tool (a panga or machete) is taken to be KSh.120.00 (East African Seed Company, Nairobi 1994). The hand-tools are assumed to have a working life of ten years. Thus, in this case, capital investment in hand-tools is required after every ten years.

7.3.4.2.2 Number of hand tools required

The total number of hand-tools required for manually cutting weed in primary and secondary canals at Mwea ISS depends upon the productivity of manual cutting. The figure is calculated as follows:

Operation	To manually cut 90,000 m of main and branch canals within a period of 30 days.
Average daily output for manual cutting (National Irrigation Board, Mwea, 1994)	50m length of main or branch canal per day
Number of labour days required to manually cut 90,000 m of main and branch canals	$\frac{90,000}{50}$ = 1,800 days
Number of labourers required to manually cut 90,000 m of main and branch canals within 30 days	$\frac{1800}{30}$ = 60 labourers
Number of hand tools required	60 tools

7.3.4.2.3 Input cost of hand tools for this maintenance programme

In total, 60 hand-tools are required for manually cutting primary and secondary canals. Assuming that any productive use elsewhere is negligible, the whole capital cost of the-tools should be allotted to the maintenance activity. This is KSh.120 x 60 = KSh.7,200. This cost will be incurred by the maintenance programme in Years each of 1, 11, 21 etc.

7.3.4.3 Labour for cutting - number required and cost

7.3.4.3.1 Cost per unit of labour

In the present example the daily rate for a manual labourer is taken to be KSh.33.42 (National Irrigation Board, Mwea 1994).

7.3.4.3.2 Number of units of labour required

The number of labour days required to maintain primary and secondary canals at Mwea ISS depends upon the productivity of manual cutting and is calculated as follows:

Number of labour days required to manually cut 90,000m of main and branch canals	1,800 days
Number of labour days required to manually cut 90,000m of main and branch canals twice a year	1,800 x 2 = 3,600 days

7.3.4.3.3 Annual input cost of labour for this maintenance programme

The annual input cost of labour is a function of the total number of labour days and the daily labour rate. It is calculated as follows:

Annual input cost of 3,600 labour days	KSh.33.42 x 3,600 = KSh.120,312

7.3.5 Life-cycle costs of the maintenance programme

The annual costs associated with the specified maintenance programme for primary and secondary canals at Mwea ISS are laid out in Table 7.6. They are based on the inputs derived in the previous section but exclude overheads. A 15-year planning period is used in this example, as explained in Section 7.4.1.

Table 7.6 Annual input costs for the specified maintenance programme

Year	Inputs	Input costs per unit (KSh)	Number of units	Annual input cost (KSh)	Total annual input cost (KSh)
1	Capital cost of excavator	9,000,000.00	5	11,250,000.00	
	Recurrent costs of excavator	701,108.63	5	876,385.79	
	Capital cost of hand-tool	120.00	60	7200.00	
	Cost of labour	33.42	3,600	120,312.00	
	Overheads	excluded			12,253, 897.79
2	Recurrent cost of excavator	701,108.63	5	876,385.79	
	Cost of labour	33.42	3,600	120,312.00	
	Overheads	excluded			996,697.79
3	Recurrent cost of excavator	701,108.63	5	876,385.79	
	Cost of labour	33.42	3,600	120,312.00	
	Overheads	excluded			996,697.79
4	Recurrent cost of excavator	701,108.63	5	876,385.79	
	Cost of labour	33.42	3,600	120,312.00	
	Overheads	excluded			996,697.79
5	Recurrent cost of excavator	701,108.63	5	876,385.79	
	Cost of labour	33.42	3,600	120,312.00	
	Overheads	excluded			996,697.79
6	Recurrent cost of excavator	701,108.63	5	876,385.79	
	Cost of labour	33.42	3,600	120,312.00	
	Overheads	excluded			996,697.79
7	Recurrent cost of excavator	701,108.63	5	876,385.79	
	Cost of labour	33.42	3,600	120,312.00	
	Overheads	excluded			996,697.79
8	Capital cost of excavator	9,000,000.00	5	11,250,000.00	
	Recurrent cost of excavator	701,108.63	5	876,385.79	
	Cost of labour	33.42	3,600	120,312.00	
	Overheads	excluded			12,246,697.79

9	Recurrent cost of excavator	701,108.63	5	876,385.79	
	Cost of labour	33.42	3,600	120,312.00	
	Overheads	excluded			996,697.79
10	Recurrent cost of excavator	701,108.63	5	876,385.79	
	Cost of labour	33.42	3,600	120,312.00	
	Overheads				996,697.79
11	Recurrent cost of excavator	701,108.63	5	876,385.79	
	Capital cost of hand-tool	120.00	60	7,200.00	
	Cost of labour	33.42	3,600	120,312.00	
	Overheads	excluded			1,003,897.79
12	Recurrent cost of excavator	701,108.63	5	876,385.79	
	Cost of labour	33.42	3,600	120,312.00	
	Overheads	excluded			996,697.79
13	Recurrent cost of excavator	701,108.63	5	876,385.79	
	Cost of labour	33.42	3,600	120,312.00	
	Overheads	excluded			996,697.79
14	Recurrent cost of excavator	701,108.63	5	876,385.79	
	Cost of labour	33.42	3,600	120,312.00	
	Overheads	excluded			996,697.79
15	Capital cost of excavator	9,000,000.00	5	11,250,000.00	
	Recurrent cost of excavator	701,108.63	5	876,385.79	
	Cost of labour	33.42	3,600	120,312.00	
	Overheads	excluded			12,246,697.79

Note: costs at 1994 constant prices, based on Mwea ISS, Kenya.

7.4 Calculation of the present value of costs

7.4.1 Rationale and procedure

The annual costs over the planning period may be converted to an equivalent present value, by applying discount factors or weights to each year's costs, based on discounted cash flow techniques to take account of the effect of time (see Box 7.1). The present value can also be expressed as an annualised cost, which represents the amount which must be recovered each year to cover the costs of the maintenance programme over the long-term. This may be recovered from charges levied, grants from government or profits from other activities.

Box 7.1 The Economic Effect of Time.

Selecting an arbitrary interest rate (say 10 %) and examining the present value of $1 at future points in time shows the present value to decline. Thus the present value of a nominal $1 received (benefit) or incurred (cost) three years from now is only 75 cents and the same nominal dollar 20 years from now has a present value of less than 15 cents. This decline in value is attributable to the opportunity cost or sacrifice in waiting for future receipts or incurring future expenditures.

With respect to waiting for returns on investment (revenues), the more distant is the time of receipt in the future, the bigger is the opportunity cost (sacrifice). Late receipt means interest earning opportunities are foregone. At 10% interest rate $100 received now would have grown at compound interest to $133.1 in three years time (see Appendix).

Therefore, having to wait for receipt of $100 for three years involves the sacrifice of $33.1 of accumulated interest. Hence each $1 received three years from now has a today's value (i.e. present value) of only 100 / 133.1 = 0.751 or about 75 cents. This means that $1's worth of revenue received three years from now should be recorded in the investment appraisal as 75 cents to reflect the economic cost of waiting.

Similarly with respect to costs, the delay or postponement of costs into the more distant future reduces their burden and hence the present value of each nominal dollar expended. Thus, delaying the payment of $100 worth of costs for three years reduces the burden in today's value to $75.

This consideration does not mean that delaying costs is necessarily a good strategy. Delays may imperil the performance of the irrigation system leading to large decreases in benefits and storing up major costs to be incurred later. Future remedial payments may well outweigh the savings from a strategy of delay.

Formally, the procedure is summarised as

$$\textit{present value} = \frac{C_1}{1+r} + \frac{C_2}{(1+r)^2} + \frac{C_3}{(1+r)^3} + \frac{C_4}{(1+r)^4} \; \ldots\ldots + \frac{C_{15}}{(1+r)^{15}}$$

where C_1 is the capital cost attributable to this function expended in Year 1.

$C_2 \ldots C_{15}$ are the annual recurrent costs (i.e. labour and inputs) tied to specific years as indicated by the numerical subscripts.

$1+r \ldots (1+r)^{15}$ are the appropriate discount rates given the assumed interest rates for Years 1-15.

The procedure is as follows:

- determine the stream of input costs for specific years (Table 7.6) over the planning period.
- apply the appropriate discount factors to bring the stream of annual costs to their present values.

- sum the annual discounted costs to yield the present value of costs for the programme.

Table 7.7 shows the calculation of the present value of the selected maintenance programme using a discount rate of 20%, and the annualised cost per kilometre. The present value of costs is KSh.17.4 million. For each kilometre cleared in each year of the investment cycle the sponsoring institution needs to recover KSh.41,352.60.

The 15 year planning period is necessarily arbitrary, but was chosen to allow the inclusion of occasional but substantial expenditures associated with particular maintenance programmes. Prolonging the period beyond 15 years was rejected because discount factors become so small that results are not seriously affected and uncertainties increase with planning period length.

The values of the present value and annualised cost depend on the selected discount rate used (see Box 7.2). The discount rate is selected to reflect the interest rate that the agency has to pay on borrowed funds, or the interest rate that it might have earned on invested funds. Its purpose is to reflect the opportunity cost of capital used in the maintenance programme. Choice of a high numerical value for the discount rate applies a more stringent or exacting financial test to the clearance strategy implying a high opportunity cost of funds used. Conversely, a low value of discount rate implies a low opportunity cost of funds.

With everything else equal, a higher discount rate reduces the present value of the costs of a maintenance programme (as described in Box 7.2). The sensitivity of the present value of costs of a programme to the choice of discount rate is a prudent test, so the present value is usually calculated for a range of discount rates.

The numerical values of the weights for values of years hence and alternative values of discount rate are presented in Appendix 2 for use in these calculations.

Table 7.7 Calculation of the present value and annualised costs for the specified maintenance programme

Year	Inputs	Input costs per unit	Number of units	Annual input cost	Annual total input cost	Discount factor 20%	Present value of costs
1	Capital cost of excavator	9,000,000.00	5	11,250,000.00			
	Annual recurrent costs of excavator	701,108.63	5	876,385.79			
	Capital cost of hand tool (panga)	120.00	60	7,200.00			
	Annual cost of labour for cutting	33.42	3,600	120,312.00			
	Overheads			excluded	12,253,897.79	0.833	10,207,496.86
2	Annual recurrent costs of excavator	701,108.63	5	876,385.79			
	Annual cost of labour for cutting	33.42	3,600	120,312.00			
	Overheads			excluded	996,697.79	0.694	691,708.26
3	Annual recurrent costs of excavator	701,108.63	5	876,385.79			
	Annual cost of labour for cutting	33.42	3,600	120,312.00			
	Overheads			excluded	996,697.79	0.579	577,088.02
4	Annual recurrent costs of excavator	701,108.63	5	876,385.79			
	Annual cost of labour for cutting	33.42	3,600	120,312.00			
	Overheads			excluded	996,697.79	0.482	480,408.33

5	Annual recurrent costs of excavator	701,108.63	5	876,385.79			
	Annual cost of labour for cutting	33.42	3,600	120,312.00			
	Overheads			excluded	996,697.79	0.402	400,672.51
6	Annual recurrent costs of excavator	701,108.63	5	876,385.79			
	Annual cost of labour for cutting	33.42	3,600	120,312.00			
	Overheads			excluded	996,697.79	0.335	333,893.76
7	Annual recurrent costs of excavator	701,108.63	5	876,385.79			
	Annual cost of labour for cutting	33.42	3,600	120,312.00			
	Overheads			excluded	996,697.79	0.279	278,078.68
8	Capital cost of excavator	9,000,000.00	5	11,250,000.00			
	Annual recurrent costs of excavator	701,108.63	5	876,385.79			
	Annual cost of labour for cutting	33.42	3,600	120,312.00			
	Overheads			excluded	12,246,697.79	0.233	2,853,480.58
9	Annual recurrent costs of excavator	701,108.63	5	876,385.79			
	Annual cost of labour for cutting	33.42	3,600	120,312.00			
	Overheads			excluded	996,697.79	0.194	193,359.37
10	Annual recurrent costs of excavator	701,108.63	5	876,385.79			
	Annual cost of labour for cutting	33.42	3,600	120,312.00			
	Overheads			excluded	996,697.79	0.162	161,465.04
11	Annual recurrent costs of excavator	701,108.63	5	876,385.79			
	Capital cost of hand-tool (panga)	120.00	60	7,200.00			
	Annual cost of labour for cutting	33.42	3,600	120,312.00			
	Overheads			excluded	1,003,897.79	0.135	135,526.20
12	Annual recurrent costs of excavator	701,108.63	5	876,385.79			
	Annual cost of labour for cutting	33.42	3,600	120,312.00			
	Overheads			excluded	996,697.79	0.112	111,630.15
13	Annual recurrent costs of excavator	701,108.63	5	876,385.79			
	Annual cost of labour for cutting	33.42	3,600	120,312.00			
	Overheads			excluded	996,697.79	0.093	92,692.89
14	Annual recurrent costs of excavator	701,108.63	5	876,385.79			
	Annual cost of labour for cutting	33.42	3,600	120,312.00			
	Overheads			excluded	996,697.79	0.078	77,742.43
15	Capital cost of excavator	9,000,000.00	5	11,250,000.00			
	Annual recurrent costs of excavator	701,108.63	5	876,385.79			
	Annual cost of labour for cutting	33.42	3,600	120,312.00			
	Overheads			excluded	12,246,697.79	0.065	796,035.36
	Sum of present value of costs						**17,391,278.45**
	Sum of present value of costs per km						**193,236.43**
	Annualised cost per km						**41,352.60**

The estimated seven-year life of a hydraulic excavator results in the purchase of new excavators in Year 15, the final year of the planning period. However the table shows that this has little impact on the present value when a 20% discount rate is used. This supports the choice of a 15-year planning period - even large expenditures this far into the future have little impact on the present value.

Box 7.2 The Economic Effect of the Size of Interest Rate.

Examination of the present value of $1 table shows that as the interest rate (discount rate) increases so the present value of $1 declines indicating that at higher rates of interest the opportunity cost of waiting increases. More interest is sacrificed and hence nominal dollars are worth less.

Selecting an arbitrary year in the future (say, Year 8) shows that the present value of $1 declines reflecting the large penalty attached to waiting as the interest rate increases.

If interest rates were very low over the planning period the economic cost of waiting would be low as little interest earning potential is lost. At very high interest rates the sacrifice of waiting is accordingly high. Likewise with costs, as interest rates increase the present value of each dollar's worth of costs declines (i.e. the burden becomes less). This reflects that with a higher interest rate over a given period each dollar will grow at compound interest to a higher figure thereby reducing the burden of each nominal dollar of cost.

7.4.2 Inflation and Investment Appraisal

It is to be noted that the rationale of discounting to present value lies in the need to incorporate the time value of money into decision-making. It is not a device for including inflation (i.e. changes in the general price level) into the calculations. Even in a world of zero inflation (i.e. constant general price level) the considerations outlined above would still hold. This is not to say that inflation is not important in the management of irrigation systems but it is not important in the context of present value investment appraisals designed to choose between alternatives.

The significance behind the assertion is that in present value calculations there is no need to incorporate forecasts of future general inflation into the cost estimates. All costs, and benefits where relevant, should be estimated at constant (i.e. today's) prices.

7.4.3 Depreciation

Provision for depreciation is not made in present value investment appraisals. The word depreciation is subject to a variety of interpretations. The most important concept of depreciation deals with the process of allocating the investment cost of fixed assets to the production expenses of operations by accounting periods.

The present value investment appraisal technique attaches the capital cost of fixed assets (say, excavators) to the year in which they are actually incurred. To include apportionment of capital costs in the calculation and provision for depreciation would thus involve double counting, that is, inclusion of capital costs twice.

CHAPTER 8

EXAMPLES AND COST COMPARISON OF MAINTENANCE STRATEGY OPTIONS

8.1 Introduction

Chapter 6 set out procedures for identifying the maintenance strategy options and a balanced programme for each option. Chapter 7 showed how to determine the annual costs and the present value and annualised costs of each option or programme using an example based on the existing practice for main and branch canals at Mwea ISS in Kenya. In this chapter we present further examples of maintenance strategy options, and cost comparisons based on data from Mwea ISS.

In analysing the maintenance strategy options, we have tended to round up the number of units of equipment (i.e. resources) used, but retained precise estimates of unit costs, to clarify the calculation process and the derivation of the figures. In practice, one would round these cost estimates, especially as the final costs are heavily dependent on the utilisation of expensive major equipment and the sharing of its costs between the different uses.

The calculations are indicative, and readers may observe ways in which they could be refined further in practice. This refinement has not been attempted here as it would tend to obscure the principles which we are trying to illustrate in these simple models.

8.2 Maintenance strategy options

Current practice at Mwea ISS (Maintenance Strategy Option A, Table 8.1) is based on desilting the main and branch canals annually by dredging using a hydraulic excavator. As well as removing sediment deposition, these operations have a major impact on weeds. In addition, weeds are cut twice per year by manual methods.

For this analysis, we consider other maintenance strategy options:

- reduce the frequency of dredging and increase the frequency of other methods of weed control
- introduce mechanical cutting of weeds using a mowing bucket on a hydraulic excavator
- introduce chemical control of weeds using herbicide applied by a knapsack sprayer
- spread operations over a number of years, for example, by desilting using hydraulic excavators every two years, operations may be spread over a two-year cycle, with half the length of canals desilted each year to achieve a more balanced use of resources.

Clearly there are other options which could be considered, but these have been chosen to illustrate the analytical methods while giving similar outputs to existing practice.

Three different maintenance strategy options are analysed, as shown in Table 8.1. The method applied is to calculate the present value of costs for each maintenance option.

The option is then subjected to alternative assumptions concerning the size of discount rate and a variety of assumptions relating to economies in input use.

Table 8.1 Maintenance strategy options, showing frequency of operations

Operation	Maintenance Strategy Options			
	A	B	C	
			canals in group I: km 0-45	canals in group II: km 46-90
Desilting				
dredging	Y1, Y2, Y3 etc.	Y1, Y3, Y5 etc.	Y1, Y3, Y5 etc.	Y2, Y4, Y6 etc.
manual desilting				
Weed control				
manual cut	Y1 x2, Y2 x2, Y3 x2 etc.	Y1 x1, Y3 x1 etc.	Y1 x1, Y3 x1 etc.	Y2 x 1, Y4 x 1 etc.
mechanical cut		Y2 x2, Y4 x2 etc.		
herbicide			Y1 x3, Y2 x3, Y4 x2, Y6 x2 etc.	Y1 x 3, Y2 x 3 Y3 x 2 Y5 x 2 etc.

Notes:

- canal groups I and II refer to the spread of operations over two years, with operations on one group of canals in one year and on the other group in the following year
- Y1 means Year 1
- x2 means two operations undertaking during the year

The essential pattern of the calculation is to identify the costs (either capital or recurrent costs) associated with each maintenance strategy option. The method follows the steps:

- identify the output to be achieved
- with respect to a specific maintenance strategy option, assign specific tasks to particular years over the assumed planning period

- using the methods exemplified in Chapter 7, calculate the input quantities and associated costs at current prices of fulfilling the tasks identified above
- assign input costs to specific years using current prices
- apply the appropriate discount factors to bring the stream of annual costs to their present values
- sum the annual discounted costs to yield the present value of costs for each maintenance strategy option
- compare and identify the least cost strategy either on a present value of costs basis or annualised cost per km basis.

8.3 Maintenance Strategy Option A

Maintenance Strategy Option A is based on the current weed management practice on primary and secondary canals at Mwea. Ordinarily the entire length of main and branch canals (approximately 90 km) is mechanically dredged between January and March every year. In addition, the entire length of these canals is manually cut on two occasions later in the year. This existing practice has been analysed in detail in Chapter 7 (Section 7.3) and the calculation of life cycle costs, present values and annualised costs was given in Table 7.7 using a 15-year planning period and a discount factor of 20%.

8.4 Maintenance Strategy Option B

The cost profile for Maintenance Strategy Option B relates to an alternative management practice for primary and secondary canals at Mwea ISS as follows:

- the entire length of main and branch canals (approximately 90 km) would be mechanically dredged every second year (i.e. Years 1,3,5, etc.) and manually cut once during each of these years
- the entire length of main and branch canals would be mechanically cut on two occasions during the interim years (i.e. Years 2,4,6, etc.).

The operations are summarised in Table 8.1. The resources required and their costs are estimated below.

8.4.1 Mowing bucket - number required and capital cost

8.4.1.1 Unit cost of mowing bucket

Capital cost of Herder MSZ300 K mowing bucket, bucket carrier and hydraulic pipes for Komatsu PC200-5 hydraulic excavator (Herder BV, Middleburg, The Netherlands, August 1995)	KSh.522,580
Carriage, insurance and freight (Herder BV, August 1995)	KSh.31,490
Capital cost of mowing bucket and attachments including carriage, insurance and freight	KSh.522,580 + KSh.31,490 = KSh.554,070

8.4.1.2 Number of mowing bucket units required

Operation	To mechanically cut 90,000 m of main and branch canals twice a year within a period of three months on each occasion.
Average output for mechanical cutting	150 m length of main or branch canal per hour.
Number of excavator hours required to mechanically cut 90,000m of main and branch canals	$\frac{90,000}{150} = 600$ hours
Standard number of operating hours for one excavator in a three month period, based on a six hour working day and 26 working days per month (National Irrigation Board, Mwea, 1994)	6 x 26 x 3 = 468 hours
Average rate of excavator utilisation	*c*. 80 %
Average number of operating hours for one hydraulic excavator in a three month period	468 x 80 % = 374 hours
Total number of excavators and mowing buckets required to mechanically cut 90,000m of main and branch canals within a period of three months	$\frac{600}{374} = 1.6 = 2$

8.4.1.3 Input cost of mowing buckets for Maintenance Strategy Option B

Capital cost of 2 MSZ300 K mowing buckets and attachments	KSh.554,070 x 2 = KSh.1,108,140
Number of months mowing buckets employed cutting 90,000m of main and branch canals twice in alternate years	six months out of 24 months
Total number of productive months mowing buckets used in 24 months	six months (Maintenance Strategy Option B) + say six months (elsewhere) = 12
Capital cost attributable to main and branch canals maintenance programme	KSh.1,108,140 x $\frac{6}{12}$ = KSh.554,070

8.4.2 Mowing bucket - annual recurrent costs

8.4.2.1 Input cost per bucket

Recurrent cost of MSZ300 K mowing bucket - 10% of capital costs (Herder BV, 1994)	KSh.522,580 x 10% = KSh.52,258

8.4.2.2 Annual input cost of mowing bucket for Maintenance Strategy Option B

Annual recurrent costs of two mowing buckets in Years 2, 4, 6 etc.	KSh.52,258 x 2 = KSh.104,516
Number of months mowing buckets employed on main and branch canals in Years 2, 4, 6 etc.	six months
Annual recurrent costs attributable to main and branch canals in Years 2, 4, 6 etc.	KSh.104,516 x $\frac{6}{12}$ = KSh.52,258

8.4.3 Hydraulic excavators - number required and capital cost

8.4.3.1 Unit cost of excavator

Capital cost of Komatsu PC200-5 hydraulic excavator including import duties (Panafrican Equipment, Nairobi, October 1994)	KSh.9,000,000

8.4.3.2 Number of excavator units required

Years 1, 3, 5 etc.:

Operation	To mechanically dredge 90,000m of main and branch canals within a period of three months
As for Maintenance Strategy Option A: total number of excavators required to mechanically dredge 90,000m of main and branch canals within a three month period each year	five excavators
Annual utilisation of excavator	5 x 3 = 15 excavator-months

Years 2, 4, 6 etc.

Operation	To mechanically cut 90,000 m of main and branch canals twice a year within a period of three months on each occasion.
As for mowing buckets: total number of excavators and mowing buckets required to mechanically cut 90,000m of main and branch canals within a period of three months	two
Annual utilisation of excavators	2 x 6 = 12 excavator-months

Therefore, the excavators are utilised on the main and branch canals more in Years 1, 3, 5 than in Years 2, 4, 6. The programme should be adjusted to take account of this, for example by dividing the canals into two groups, with dredging and manual cutting undertaken on half the length each year, and mechanical cutting on the other half, alternating each year. This would also spread the use of the specialist mowing buckets.

To simplify the illustrative analysis however we have not done this. We assume that five excavators are purchased in Year 1 for this maintenance work, and assigned to main and branch canal maintenance for 15 excavator-months per year, every year, and used productively elsewhere for the remaining 45 excavator-months each year. Therefore 25% of the capital costs of the excavators are charged to Maintenance Strategy Option B. The recurrent costs however are dominated by hourly consumption of fuel and lubricants, so we have charged 25% of the annual recurrent costs to Maintenance Strategy Option B in Years 1, 3, 5 etc. but only 20% in Years 2, 4, 6. These utilisation shares are rounded figures, and depend on how the excavators are used elsewhere. Different assumptions on other uses would give different results.

8.4.3.3 Input cost of excavators for Maintenance Strategy Option B

Capital cost of five PC200-5 hydraulic excavators	KSh.9,000,000 x 5 = KSh.45,000,000
Assignment to main and branch canal maintenance	15 excavator-months = 25%
Capital cost attributable to main and branch canal maintenance	KSh.45,000,000 x 0.25 = KSh.11,250,000

8.4.4 Hydraulic excavator - annual recurrent costs

8.4.4.1 Input costs per excavator

Annual recurrent costs for a PC200-5 hydraulic excavator.

As for Maintenance Strategy Option A: total annual recurrent cost	KSh.701,108.63

8.4.4.2 Annual input cost of excavators for Maintenance Strategy Option B

Annual recurrent costs of five PC200-5 hydraulic excavators	KSh.701,108.63 x 5 = KSh.3,505,543.10
Utilisation dredging main and branch canals in Year 1, 3, 5 etc.	15 excavator-months = 25%
Annual recurrent costs attributable to main and branch canals in Year 1, 3 ,5 etc.	KSh.3,505,543.10 x 0.25 = KSh.876,385.79
Utilisation on mechanical cutting of main and branch canals in Years 2, 4, 6 etc.	12 excavator-months = 20 %
Annual recurrent costs attributable to main and branch canals in Year 2, 4, 6 etc.	KSh.3,505,543.10 x 0.20 = KSh.701,108

8.4.5 Hand tools (panga) - number required and capital cost

8.4.5.1 Capital cost of hand-tool

Capital cost of panga (East African Seed Company, Nairobi, 1994)	KSh.120

8.4.5.2 Number of hand tools required

Operation	To manually cut 90,000 m of main and branch canals within a period of 30 days
Average daily output for manual cutting (National Irrigation Board, Mwea, 1994)	50 m length of main or branch canal per day per labourer.
Number of labour days required to manually cut 90,000 m of main and branch canals once a year	$\frac{90,000}{50} = 1,800$ days
Number of labourers required to manually cut 90,000m of main and branch canals within a period of 30 days	$\frac{1,800}{30} = 60$ labourers
Number of hand tools required	60 tools

8.4.5.3 Input cost of hand tools for Maintenance Strategy Option B

Capital cost of hand tools (all of which is attributed to maintenance of main and branch canals)	KSh.120 x 60 = KSh.7,200

8.4.6 Labour for cutting - number required and cost

8.4.6.1 Input cost per unit of labour

Cost of one labour day (National Irrigation Board, Mwea, 1994)	KSh.33.42

8.4.6.2 Number of units of labour required

Number of labour days required to manually cut 90,000m of main and branch canals once a year	1,800 days

8.4.6.3 Annual input cost of labour for Maintenance Strategy Option B

Annual input cost of 1,800 labour days in Years 1, 3, 5 etc.	KSh.33.42 x 1,800 = KSh.60,156 per year

8.4.7 Life cycle costs of Maintenance Strategy Option B

The annual costs of this option are shown in Table 8.2, together with the present value and annualised cost. These are calculated using a 15-year planning period and a discount factor of 20%.

Table 8.2 Life cycle costs, Maintenance Strategy Option B - less dredging, manual/mechanical cutting

Year	Inputs	Input costs per unit	Number of units	Annual input cost	Annual input cost	Discount rate 20%	Present value of costs
1	Capital cost of excavator	9,000,000.0	5	11,250,000.0			
	Annual recurrent costs of excavator	701,108.63	5	876,385.79			
	Capital cost of hand tool (panga)	120.00	60	7,200.00			
	Annual cost of labour for cutting	33.42	1,800	60,156.00			
	Overheads			excluded	12,193,741.7	0.833	10,157,386.91
2	Annual recurrent costs of excavator	701,108.63	2	701,108.63			
	Capital cost of mowing bucket	554,070.00	2	554,070.00			
	Annual recurrent costs of mowing	52,258.00	2	52,258.00			
	Overheads			excluded	1,307,436.63	0.694	907,361.02
3	Annual recurrent costs of excavator	701,108.63	5	876,385.79			
	Annual cost of labour for cutting	33.42	1,800	60,156.00			
	Overheads			excluded	936,541.79	0.579	542,257.69
4	Annual recurrent costs of excavator	701,108.63	2	701,108.63			
	Annual recurrent costs of mowing	52,258.00	2	52,258.00			
	Overheads			excluded	753,366.63	0.482	363,122.72
5	Annual recurrent costs of excavator	701,108.63	5	876,385.79			
	Annual cost of labour for cutting	33.42	1,800	60,156.00			
	Overheads			excluded	936,541.79	0.402	376,489.80
6	Annual recurrent costs of excavator	701,108.63	2	701,108.63			
	Annual recurrent costs of mowing	52,258.00	2	52,258.00			
	Overheads			excluded	753,366.63	0.335	252,377.82
7	Annual recurrent costs of excavator	701,108.63	5	876,385.79			
	Annual cost of labour for cutting	33.42	1,800	60,156.00			
	Overheads			excluded	936,541.79	0.279	261,295.16
8	Capital cost of excavator	9,000,000.0	5	11,250,000.0			
	Annual recurrent costs of excavator	701,108.63	2	701,108.63			
	Capital cost of mowing bucket	554,070.00	2	554,070.00			
	Annual recurrent costs of mowing	52,258.00	2	52,258.00			
	Overheads			excluded	12,557,436.6	0.233	2,925,882.73
9	Annual recurrent costs of excavator	701,108.63	5	876,385.79			
	Annual cost of labour for cutting	33.42	1,800	60,156.00			
	Overheads			excluded	936,541.79	0.194	181,689.11
10	Annual recurrent costs of excavator	701,108.63	2	701,108.63			
	Annual recurrent costs of mowing	52,258.00	2	52,258.00			
	Overheads			excluded	753,366.63	0.162	122,045.39
11	Annual recurrent costs of excavator	701,108.63	5	876,385.79			
	Capital cost of hand-tool (panga)	120.00	60	7,200.00			
	Annual cost of labour for cutting	33.42	1,800	60,156.00			
	Overheads			excluded	943,741.79	0.135	127,405.14
12	Annual recurrent costs of excavator	701,108.63	2	701,108.63			
	Annual recurrent costs of mowing	52,258.00	2	52,258.00			
	Overheads			excluded	753,366.63	0.112	84,377.06
13	Annual recurrent costs of excavator	701,108.63	5	876,385.79			
	Annual cost of labour for cutting	33.42	1,800	60,156.00			
	Overheads			excluded	936,541.79	0.093	87,098.39
14	Annual recurrent costs of excavator	701,108.63	2	701,108.63			
	Capital cost of mowing bucket	554,070.00	2	554,070.00			
	Annual recurrent costs of mowing	52,258.00	2	52,258.00			
	Overheads			excluded	1,307,436.63	0.078	101,980.06
15	Capital cost of excavator	9,000,000.0	5	11,250,000.0			
	Annual recurrent costs of excavator	701,108.63	5	876,385.79			
	Annual cost of labour for cutting	33.42	1,800	60,156.00			
	Overheads			excluded	12,186,541.7	0.065	792,125.22
	Sum of present value of costs						**17,282,894.22**
	Sum of present value of costs per						**192,032.16**
	Annualised cost per km						**41,094.88**

8.5 Maintenance Strategy Option C

The cost profile for Maintenance Strategy Option C relates to a second hypothetical management practice for primary and secondary canals at Mwea ISS:

- the main and branch canals would be mechanically dredged every second year (e.g. Years 1, 3, 5, etc.) and manually cut once during each of these years
- the main and branch canals would be treated with herbicide on three occasions during the first two years, and on two occasions during the interim years, commencing in Year 4 (e.g. Years 4, 6, 8, etc.)
- to spread the use of resources and reduce the peak demand, particularly the number of excavators required, the canals are divided into two groups, with dredging and manual cutting undertaken on half the length (approximately 45 km) each year.

The operations are summarised in Table 8.1. The required resources and their costs are estimated below.

8.5.1 Hydraulic excavators - number required and capital cost

8.5.1.1 Unit cost of excavator

Capital cost of PC200-5 hydraulic excavator	KSh.9,000,000

8.5.1.2 Number of excavator units required

Operation	To mechanically dredge 45,000m of main and branch canals within a period of three months
Average output for mechanical dredging	50m length of main or branch canal per hour.
Number of excavator hours required to mechanically dredge 45,000m of main and branch canals	$\frac{45,000}{50} = 900$ hours
Standard number of operating hours for one excavator in a three month period, based on a six hour working day and 26 working days per month	6 x 26 x 3 = 468 hours
Average rate of excavator utilisation	*c*. 80 %
Average number of operating hours for one hydraulic excavator in a three month period	468 x 80 % = 374 hours
Total number of excavators required to mechanically dredge 45,000m of main and branch canals within a three month period each year	$\frac{900}{374} = 2.4$ excavators

Therefore it will be necessary to purchase three hydraulic excavators.

8.5.1.3 Input cost of excavators for Maintenance Strategy Option C

Capital cost of three PC200-5 hydraulic excavators	KSh.9,000,000 x 3 = KSh.27,000,000
Number of months excavators employed dredging main and branch canals each year	three months (rounded up from 2.4 months)
Total number of productive months excavators used each year	three months (Maintenance Option C) + say nine months (elsewhere) = 12
Capital cost attributable to main and branch canals maintenance	KSh.27,000,000 x $\frac{3}{12}$ = KSh.6,750,000

8.5.2 Hydraulic excavator - annual recurrent costs

8.5.2.1 Input costs per excavator

Annual recurrent costs for a PC200-5 hydraulic excavator.

as for Maintenance Strategy Option A:
total annual recurrent cost KSh.701,108.63

8.5.2.2 Annual input cost of excavators for Maintenance Strategy Option C

Annual recurrent costs of three hydraulic excavators	KSh.701,108.63 x 3 = KSh.2,103,325.89
Utilisation dredging main and branch canals each year	nine excavator-months = 25%
Annual recurrent costs attributable to main and branch canals each year	KSh.2,103,325.89 x 0.25 = KSh.525,831.47

8.5.3 Hand tools (panga) - number required and capital cost

8.5.3.1 Capital cost of hand-tool

Capital cost of panga (East African Seed Company, Nairobi, 1994)	KSh.120

8.5.3.2 Number of hand tools required

Operation	To manually cut 45,000 m of main and branch canals within a period of 30 days.

Average daily output for manual cutting (National Irrigation Board, Mwea, 1994)	50m length of main or branch canal per day
Number of labour days required to manually cut 45,000 m of main and branch canals	$\frac{45,000}{50} = 900$ days
Number of labourers required to manually cut 45,000 m of main and branch canals within 30 days	$\frac{900}{30} = 30$ labourers
Number of hand tools required	30 tools

8.5.3.3 Annual input cost of hand tools for Maintenance Strategy Option C

Capital cost of 30 hand tools (all attributed to maintenance of main and branch canals)	KSh.120 x 30 = KSh.3600

8.5.4 Labour for cutting - number required and cost

8.5.4.1 Input cost per unit of labour

Cost of one labour day (National Irrigation Board, Mwea, 1994)	KSh.33.42

8.5.4.2 Number of units of labour required

Number of labour days required to manually cut 45,000m of main and branch canals once per year	900 days

8.5.4.3 Annual input cost of labour for cutting for Maintenance Strategy Option C

Annual input cost of 900 labour days	KSh.33.42 x 900 = KSh.30,078

8.5.5 Knapsack sprayer - number required and capital cost

8.5.5.1 Unit cost of knapsack sprayer

Capital cost of Cooper-Pegler CP3 knapsack sprayer (Agromed, Nairobi, October 1994)	KSh.6,700

8.5.5.2 Number of knapsack sprayers required

Operation	To spray simultaneously, a 2.5 m swathe along both banks of 45,000 m of main and branch canals, within a period of 30 days.
Total area to be sprayed each treatment	2.5 x 2 x 45,000 = 225,000 m^2 = 22.5 ha

Time taken to discharge herbicide from knapsack sprayer, based on flow rate of 2.5 litre/min and knapsack volume of 20 litre per tank	$\frac{20}{2.5} = 8$ minutes
Total area sprayed over eight minute period, based on walking speed of 1 m/s and spray width of 1.5 m	1 x 1.5 x 60 x 8 = 720 m^2
Total time required to mix and discharge herbicide, based on a mixing time of five minutes	5 + 8 = 13 minutes
Number of tanks discharged during one working day, based on an eight hour day, a 50 minute working hour, and an allowance of one hour for spray calibration	$(8-1) \times \frac{50}{13} = 27$ tanks
Total area sprayed during one working day	720 x 27 = 19,440 m^2
Number of days required to treat 45,000 m main and branch canals	$\frac{225{,}000}{19{,}440} = 12$ days
Year 1: requirement for 2 tasks undertaken during one month	24 days
Number of knapsack sprayers required (minimum two, to provide capability in case of breakdown)	two sprayers

8.5.5.3 Input cost of knapsack sprayers for Maintenance Strategy Option C

Capital cost of two CP3 knapsack sprayers	KSh.6,700 x 2 = KSh.13,400
Annual number of days knapsack sprayers required for spraying main and branch canals three times per year	24 x 3 = 72 days
Assume sprayers are used 50% on main and branch canals, and 50% on other tasks	
Capital cost attributable to main and branch canals maintenance	KSh.13,400 x 0.50 = KSh.6,700

8.5.6 Herbicide - quantity required and cost

8.5.6.1 Unit cost of herbicide

Capital cost of one litre of Roundup (Twiga Chemical Industries Limited, Nairobi, October 1994)	KSh.750

8.5.6.2 Number of units of herbicide required

Operation	To treat with herbicide a 2.5 m swathe along both banks of 45,000m

	of main and branch canals.
Total area to be sprayed	2.5 x 2 x 45,000 = 225,000 m^2 = 23 ha
Volume of herbicide required to treat 23 ha, based on application rate of 5 litre/ha	5 x 23 = 115 litre

8.5.6.3 Input cost of herbicide for Maintenance Strategy Option C

Operation cost of 115 litre Roundup	KSh.750 x 115 = KSh.86,250

Annual costs will vary with the number of tasks to be undertaken each year.

8.5.7 Labour for spraying - number required and cost

8.5.7.1 Input cost per unit of labour for spraying

Cost of one labour day	KSh.44.23

8.5.7.2 Number of units of labour required for spraying

Number of labour days required to spray 45,000 m of main and branch canals	12 days

8.5.7.3 Input cost of labour for spraying for Maintenance Strategy Option C

Operation input cost of 12 days labour for spraying	KSh.44.23 x 12 = KSh.530.76

Annual costs will vary with the number of operations to be undertaken each year.

8.5.7.4 Input cost of spraying (i.e. herbicide and labour) for Maintenance Strategy Option C

Operation cost for 45,000 m	KSh.86,250 + 530.76 = KSh.86,780.76

8.5.8 Life cycle costs of Maintenance Strategy Option C

The annual costs of this option are shown in Table 8.3, together with the present value and annualised cost. These are calculated using a 15-year planning period and a discount factor of 20%.

Table 8.3 Life cycle costs, Maintenance Strategy Option C - reduced dredging, manual/chemical control

Year	Inputs	Input costs per unit	Number of units	Annual input cost	Annual total input cost	Discount rate 20%	Present value of costs
1	Capital cost of excavator	9,000,000.00	3	6,750,000.00			
	Capital cost of hand-tool (panga)	120.00	30	3,600.00			
	Capital cost of knapsack sprayer	6,700.00	2	6,700.00			
	Annual recurrent costs of excavator	701,108.63	3	525,831.47			
	Annual cost of labour for cutting	33.42	900	30,078.00			
	Spraying (operation)	86,780.76	6	520,684.56			
	Overheads	excluded			7,836,894.03	0.833	6,528,132.73
2	Annual recurrent costs of excavator	701,108.63	3	525,831.47			
	Annual cost of labour for cutting	33.42	900	30,078.00			
	Spraying (operation)	86,780.76	6	520,684.56			
	Overheads	excluded			1,076,594.03	0.694	747,156.26
3	Annual recurrent costs of excavator	701,108.63	3	525,831.47			
	Annual cost of labour for cutting	33.42	900	30,078.00			
	Spraying (operation)	86,780.76	2	173,561.52			
	Overheads	excluded			729,470.99	0.579	422,363.70
4	Annual recurrent costs of excavator	701,108.63	3	525,831.47			
	Annual cost of labour for cutting	33.42	900	30,078.00			
	Spraying (operation)	86,780.76	2	173,561.52			
	Overheads	excluded			729,470.99	0.482	351,605.02
5	Annual recurrent costs of excavator	701,108.63	3	525,831.47			
	Annual cost of labour for cutting	33.42	900	30,078.00			
	Spraying (operation)	86,780.76	2	173,561.52			
	Overheads	excluded			729,470.99	0.402	293,247.34
6	Annual recurrent costs of excavator	701,108.63	3	525,831.47			
	Annual cost of labour for cutting	33.42	900	30,078.00			
	Spraying (operation)	86,780.76	2	173,561.52			
	Overheads	excluded			729,470.99	0.335	244,372.78
7	Annual recurrent costs of excavator	701,108.63	3	525,831.47			
	Annual cost of labour for cutting	33.42	900	30,078.00			
	Spraying (operation)	86,780.76	2	173,561.52			
	Overheads	excluded			729,470.99	0.279	203,522.41
8	Capital cost of excavator	9,000,000.00	3	6,750,000.00			
	Annual recurrent costs of excavator	701,108.63	3	525,831.47			
	Annual cost of labour for cutting	33.42	900	30,078.00			
	Spraying (operation)	86,780.76	2	173,561.52			
	Overheads	excluded			7,479,470.99	0.233	1,742,716.74
9	Annual recurrent costs of excavator	701,108.63	3	525,831.47			
	Annual cost of labour for cutting	33.42	900	30,078.00			
	Spraying (operation)	86,780.76	2	173,561.52			
	Overheads	excluded			729,470.99	0.194	141,517.37
10	Capital cost of knapsack sprayer	6,700.00	2	6,700.00			
	Annual recurrent costs of excavator	701,108.63	3	525,831.47			
	Annual cost of labour for cutting	33.42	900	30,078.00			
	Spraying (operation)	86,780.76	2	173,561.52			
	Overheads	excluded			736,170.99	0.162	119,259.70
11	Capital cost of hand-tool (panga)	120.00	30	3,600.00			
	Annual recurrent costs of excavator	701,108.63	3	525,831.47			
	Annual cost of labour for cutting	33.42	900	30,078.00			
	Spraying (operation)	86,780.76	2	173,561.52			
	Overheads	excluded			733,070.99	0.135	98,964.58

12	Annual recurrent costs of excavator	701,108.63	3	525,831.47			
	Annual cost of labour for cutting	33.42	900	30,078.00			
	Spraying (operation)	86,780.76	2	173,561.52			
	Overheads	excluded			729,470.99	0.112	81,700.75
13	Annual recurrent costs of excavator	701,108.63	3	525,831.47			
	Annual cost of labour for cutting	33.42	900	30,078.00			
	Spraying (operation)	86,780.76	2	173,561.52			
	Overheads	excluded			729,470.99	0.093	67,840.80
14	Annual recurrent costs of excavator	701,108.63	3	525,831.47			
	Annual cost of labour for cutting	33.42	900	30,078.00			
	Spraying (operation)	86,780.76	2	173,561.52			
	Overheads	excluded			729,470.99	0.078	56,898.74
15	Capital cost of excavator	9,000,000.00	5	11,250,000.00			
	Annual recurrent costs of excavator	701,108.63	3	525,831.47			
	Annual cost of labour for cutting	33.42	900	30,078.00			
	Spraying (operation)	86,780.76	2	173,561.52			
	Overheads	excluded			11,979,470.99	0.065	778,665.61
	Sum of present value of costs						**11,877,964.54**
	Sum of present value of costs per km						**131,977.38**
	Annualised cost per km						**28,243.16**

8.6 Cost comparisons

Table 8.4 shows the present values for the three maintenance strategy options over the 15 year planning period, and annualised costs per kilometre.

Table 8.4 Comparison of Maintenance Strategy Options

Maintenance strategy option	Present value (KSh.million)	Annualised costs (KSh. per km)
A	17.4	41,353
B	17.3	41,095
C	11.9	28,243

Maintenance Strategy Option A (Table 8.1) represents the current weed management practice at Mwea ISS. It requires the annual dredging over a three month period of 90 km of canals. Additionally, the same length of canal is manually cut on two later occasions each year. This maintenance strategy option requires the use of five excavators and may be viewed as capital intensive. Details of the justifications of inputs and their costs are presented in Chapter 6 - Preparation of maintenance programmes.

Maintenance Strategy Option B (Table 8.1) presents an alternative weed management option in which the 90 km would be mechanically dredged in alternate years with weed control by manual cutting during these same alternate years and mechanical cutting the other years. The similarity of the Present Value of costs results for Maintenance strategy options A and B is attributable to the preponderance of capital costs of excavators in each case.

Maintenance Strategy Option C (Table 8.1) is similar to B in the pattern of alternate year dredging and manual cutting. It differs by the replacement of mechanical cutting by herbicide treatment in years in which dredging and manual cutting do not occur, and by the spread of operations over two years by dividing the canals into two groups.

The general cost advantage of Maintenance Strategy Option C over Maintenance strategy Options A and B is attributable to the substantial reduction in hydraulic excavator costs associated with less frequent mechanical operations (i.e. dredging and mechanical cutting).

The calculations are illustrative of feasible alternative means of achieving a common level of maintenance. They are not to be interpreted as incontrovertible evidence that Maintenance Strategy Option C is an 'ideal' programme. Considerations of environmental protection, public health or labour availability may preclude such an option. Rather the calculations are intended to convey the method by which the process of identifying the least cost maintenance strategy option could be undertaken giving due consideration to local conditions and constraints. In this case they also show that the hydraulic excavator inputs have a major impact on the maintenance costs.

8.7 Sensitivity analyses

8.7.1 Effect of variable discount factors on annualised costs

The calculations presented in Tables 8.1 to 8.3 use the 20% discount rate. Such a high figure is justified by the likely high opportunity cost of time to the irrigation agency. The effect of using different discount rates is shown in Table 8.5. In all cases the costs of Maintenance Strategy Options A and B are comparable, while C is considerably cheaper.

Table 8.5 Annualised costs (in KSh. per km) of main and branch canals maintained by different management practices.

Maintenance strategy option	Discount Factor		
	10%	20%	30%
A	37,491.77	41,352.60	46,279.22
B	37,145.44	41,094.88	46,123.83
C	26,403.55	28,243.16	31,179.72

8.7.2 Effect of under utilisation of equipment

All the above calculations assume that the hydraulic excavators are used productively elsewhere for the nine months of the year when they are not required for the canal maintenance programme. If this is not the case, the maintenance programme will have to bear a larger share of the capital cost of the excavators, causing significant increases in the annualised cost.

For example, consider the effect on Maintenance Strategy Option A if the five excavators are used three months per year on canal maintenance and only six months elsewhere, strategy i.e. standing idle for three months because of the weather or lack of work. The 10,500 hour excavator life would not be reached until Year 10, but the cost share to the maintenance programme would be 33% instead of 25%. This results in a capital expenditure of KSh.15 million in Years 1 and 10. Similarly the lower running hours would reduce the estimated annual recurrent cost to KSh.545,079 per excavator, but again 33% would be borne by the canal maintenance programme. The resulting life cycle costs are given in Table 8.6, which shows that the less efficient utilisation of the hydraulic excavators increases the annualised cost by more than 13%.

Table 8.6 Life cycle costs of Maintenance Strategy Option A with less efficient utilisation of excavators.

Year	Inputs	Input costs per unit	Number of unit	Annual input cost	Annual total input cost	Discount rate 20%	Present value of costs
1	Capital cost of excavator	9,000,000.00	5	15,000,000.00			
	Annual recurrent costs of excavator	545,078.63	5	908,464.38			
	Capital cost of hand tool (panga)	120.00	60	7,200.00			
	Annual cost of labour for cutting	33.42	3,600	120,312.00			
	Overheads			excluded	16,035,976.38	0.833	13,357,968.33
2	Annual recurrent costs of excavator	545,078.63	5	908,464.38			
	Annual cost of labour for cutting	33.42	3,600	120,312.00			
	Overheads			excluded	1,028,776.38	0.694	713,970.81
3	Annual recurrent costs of excavator	545,078.63	5	908,464.38			
	Annual cost of labour for cutting	33.42	3,600	120,312.00			
	Overheads			excluded	1,028,776.38	0.579	595,661.53
4	Annual recurrent costs of excavator	545,078.63	5	908,464.38			
	Annual cost of labour for cutting	33.42	3,600	120,312.00			
	Overheads			excluded	1,028,776.38	0.482	495,870.22
5	Annual recurrent costs of excavator	545,078.63	5	908,464.38			
	Annual cost of labour for cutting	33.42	3,600	120,312.00			
	Overheads			excluded	1,028,776.38	0.402	413,568.11
6	Annual recurrent costs of excavator	545,078.63	5	908,464.38			
	Annual cost of labour for cutting	33.42	3,600	120,312.00			
	Overheads			excluded	1,028,776.38	0.335	344,640.09
7	Annual recurrent costs of excavator	545,078.63	5	908,464.38			
	Annual cost of labour for cutting	33.42	3,600	120,312.00			
	Overheads			excluded	1,028,776.38	0.279	287,028.61
8	Annual recurrent costs of excavator	545,078.63	5	908,464.38			
	Annual cost of labour for cutting	33.42	3,600	120,312.00			
	Overheads			excluded	1,028,776.38	0.233	239,704.90

9	Annual recurrent costs of excavator	545,078.63	5	908,464.38			
	Annual cost of labour for cutting	33.42	3,600	120,312.00			
	Overheads			excluded	1,028,776.38	0.194	199,582.62
10	Capital cost of excavator	9,000,000.00	5	15,000,000.00			
	Annual recurrent costs of excavator	545,078.63	5	908,464.38			
	Annual cost of labour for cutting	33.42	3,600	120,312.00			
	Overheads			excluded	16,028,776.38	0.162	2,596,661.77
11	Annual recurrent costs of excavator	545,078.63	5	908,464.38			
	Capital cost of hand-tool (panga)	120.00	60	7,200.00			
	Annual cost of labour for cutting	33.42	3,600	120,312.00			
	Overheads			excluded	1,035,976.38	0.135	139,856.81
12	Annual recurrent costs of excavator	545,078.63	5	908,464.38			
	Annual cost of labour for cutting	33.42	3,600	120,312.00			
	Overheads			excluded	1,028,776.38	0.112	115,222.95
13	Annual recurrent costs of excavator	545,078.63	5	908,464.38			
	Annual cost of labour for cutting	33.42	3,600	120,312.00			
	Overheads			excluded	1,028,776.38	0.093	95,676.20
14	Annual recurrent costs of excavator	545,078.63	5	908,464.38			
	Annual cost of labour for cutting	33.42	3,600	120,312.00			
	Overheads			excluded	1,028,776.38	0.078	80,244.56
15	Annual recurrent costs of excavator	545,078.63	5	908,464.38			
	Annual cost of labour for cutting	33.42	3,600	120,312.00			
	Overheads			excluded	1,028,776.38	0.065	66,870.46
	Sum of present value of costs						**19,742,527.97**
	Sum of present value of costs per km						**219,361.42**
	Annualised cost per km						**46,943.34**

8.7.3 Effect of increased levels of efficiency on annualised costs

We considered the effects on Maintenance Strategy Option C of increased efficiency in use of herbicide and labour, but these made little difference because the costs are dominated by the hydraulic excavator requirements.

8.8 Labour-based desilting operations

8.8.1 Maintenance strategy

An alternative way to reduce the hydraulic excavator inputs would be to use manual labour for desilting when canals are not in use. This option is illustrated by Maintenance Strategy Option A2 which is a more labour intensive variant of Maintenance Strategy Option A. The number of available excavators is reduced from five to three and this shortfall in capital equipment is compensated for by an increase in labour.

Labour productivity in hand-digging depends on a number of factors both physical and behavioural. Physical conditions such as type of soil, weight, wetness and disposal distance and height will effect productivity. Likewise, behavioural factors such as motivation, incentives, sanctions, payment mechanism and strength of labourers will all have a bearing on productivity. For management, this reinforces the requirement for sound training, supervision and monitoring of labour performance. Productivity may be enhanced by the effective deployment of incentives and sanctions. Targets and bonus payments may be central in this deployment.

Empirical evidence (De Veen 1980) suggests that productivities within the range

1.5 m^3 to 3 m^3 per labour-day are realistic given the physical and behavioural conditions encountered in developing countries. Canal desilting conditions will generally be relatively difficult. The linear output per labour-day will depend on the size of the canal and the depth of silt, as well as the factors mentioned above. In Maintenance Strategy Option A2, we assume a desilting rate of 3 m length of canal per labour-day, which is probably a fairly low estimate.

8.8.2 Calculations of input requirements

Hydraulic excavator dredges 50 m length of channel per hour, working six hours per day.

Therefore hydraulic excavator achieves 300 m per day.

Hydraulic excavator works 26 days per month for three months

= 300 m x 26 days x 3 months = 23,400m

Assume hydraulic excavator has an 80% utilisation rate

output = 23,400 x 0.8 = 18,720 (say 18,700 m) in three months.

Therefore three excavators would achieve 18,700 x 3 = 56,100m.

Task is 90,000 m to be excavated in total.

Therefore 90,000 - 56,100 = 33,840 m to be excavated by men.

Assuming one man does 3m per day

$\frac{33,840}{3}$ = 11,280 man days needed.

11,280 man days x KSh.33.42 = KSh.375,975

These figures are the <u>extra</u> labour costs incurred due to the substitution of extra labour for the two machines reduction.

The original labour costs for cutting weeds will still be incurred and must be added to the extra labour costs to arrive at the annual cost of labour:

11,280	+	3,600	=	14,880
extra man days		original man days		total labour input

14,880	x	KSh.33.42	=	KSh.497,289
labour input		daily wage rate		Annual labour input cost

8.8.3 Life-cycle costs

Table 8.7 shows the annual costs, and the corresponding present value and annualised cost of this maintenance programme. At the 20% discount rate Maintenance Option A2 records a Present Value of costs slightly in excess of KSh.12.4 million. For each kilometre cleared in each year of the investment cycle the sponsoring institution needs to recover KSh.29,562.64. This may be recovered from charges levied, grants etc. from government or profits from other activities.

Maintenance Strategy Option A2 is therefore an attractive alternative, if a labour-based desilting programme is feasible (as on the Chisumbanje case study described in Chapter 2 and in particular if the requirements can be met for labour availability and for access to the canals. The costs are comparable to those of Maintenance Strategy Option C.

Table 8.7 Life cycle costs, Maintenance Strategy Option A2 -reduced dredging, manual desilting/cutting

Year	Inputs	Input costs per unit	Number of units	Annual input cost	Annual total input cost	Discount rate 20%	Present value of costs
1	Capital cost of excavator	9,000,000.00	3	6,750,000.00			
	Annual recurrent costs of excavator	701,108.63	3	525,831.47			
	Capital cost of hand tool	120.00	125	15,000.00			
	Annual cost of labour	33.42	14,880	497,289.60			
	Overheads			excluded	7,788,121.07	0.833	6,487,504.85
2	Annual recurrent costs of excavator	701,108.63	3	525,831.47			
	Annual cost of labour	33.42	14,880	497,289.60			
	Overheads			excluded	1,023,121.07	0.694	710,046.02
3	Annual recurrent costs of excavator	701,108.63	3	525,831.47			
	Annual cost of labour	33.42	14,880	497,289.60			
	Overheads			excluded	1,023,121.07	0.579	592,387.10
4	Annual recurrent costs of excavator	701,108.63	3	525,831.47			
	Annual cost of labour	33.42	14,880	497,289.60			
	Overheads			excluded	1,023,121.07	0.482	493,144.36
5	Annual recurrent costs of excavator	701,108.63	3	525,831.47			
	Annual cost of labour	33.42	14,880	497,289.60			
	Overheads			excluded	1,023,121.07	0.402	411,294.67
6	Annual recurrent costs of excavator	701,108.63	3	525,831.47			
	Annual cost of labour	33.42	14,880	497,289.60			
	Overheads			excluded	1,023,121.07	0.335	342,745.56
7	Annual recurrent costs of excavator	701,108.63	3	525,831.47			
	Annual cost of labour	33.42	14,880	497,289.60			
	Overheads			excluded	1,023,121.07	0.279	285,450.78
8	Capital cost of excavator	9,000,000.00	3	6,750,000.00			
	Annual recurrent costs of	701,108.63	3	525,831.47			

	excavator						
	Annual cost of labour	33.42	14,880	497,289.60			
	Overheads			excluded	7,773,121.07	0.233	1,811,137.21
9	Annual recurrent costs of excavator	701,108.63	3	525,831.47			
	Annual cost of labour	33.42	14,880	497,289.60			
	Overheads			excluded	1,023,121.07	0.194	198,485.49
10	Annual recurrent costs of excavator	701,108.63	3	525,831.47			
	Annual cost of labour	33.42	14,880	497,289.60			
	Overheads			excluded	1,023,121.07	0.162	165,745.61
11	Annual recurrent costs of excavator	701,108.63	3	525,831.47			
	Capital cost of hand-tool	120.00	125	15,000.00			
	Annual cost of labour	33.42	14,880	497,289.60			
	Overheads			excluded	1,038,121.07	0.135	140,146.34
12	Annual recurrent costs of excavator	701,108.63	3	525,831.47			
	Annual cost of labour	33.42	14,880	497,289.60			
	Overheads			excluded	1,023,121.07	0.112	114,589.56
13	Annual recurrent costs of excavator	701,108.63	3	525,831.47			
	Annual cost of labour	33.42	14,880	497,289.60			
	Overheads			excluded	1,023,121.07	0.093	95,150.26
14	Annual recurrent costs of excavator	701,108.63	3	525,831.47			
	Annual cost of labour	33.42	14,880	497,289.60			
	Overheads			excluded	1,023,121.07	0.078	79,803.44
15	Capital cost of excavator	9,000,000.00	3	6,750,000.00			
	Annual recurrent costs of excavator	701,108.63	3	525,831.47			
	Annual cost of labour	33.42	14,880	497,289.60			
	Overheads			excluded	7,773,121.07	0.065	505,252.87
	Sum of present value of costs						**12,432,884.14**
	Sum of present value of costs per km						**138,143.16**
	Annualised cost per km						**29,562.64**

References

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CHAPTER 9
INSTITUTIONS AND MANAGEMENT

9.1 Introduction

The irrigation management context and goals were introduced in Chapters 1 and 5 and illustrated in Figures 1.2 and 1.3. This chapter is concerned with four specific aspects of irrigation management institutions as they relate to the management of maintenance of irrigation and drainage channels:

- Organisational structures
- Maintenance responsibilities
- Financing and cost recovery of operation and maintenance expenditure
- Data collection and monitoring

9.2 Organisational structures

9.2.1 Introduction

Sagardoy (1982) described two types of organisational structure: the segregated structure and the integrated structure. These are related to a hierarchy of goals assumed for management of irrigation systems: greater agricultural production, greater income, and betterment of farmers' welfare. Specific goals will vary between irrigation schemes, and organisational structures evolve for various reasons, but the distinction between segregated and integrated structures is generally useful.

9.2.2 Segregated structure

In a segregated structure several organisations are involved, each of which is concerned with a specific area of activity and one (or a few) related goals. For example, an Irrigation Department has the goal of appropriate use of water, and an Agricultural Department the appropriate use of other inputs. It is assumed that the interaction of these line agencies working independently will produce the overall goal of improving farmers' welfare. An example of a typical segregated organisational structure is given in Figure 9.1.

The advantages of this approach are its simplicity and focus on one goal which is related to the organisation's particular area of expertise.

One disadvantage is that the services provided may be more dependent on the national norms applied by the line agencies than on the specific needs of farmers within the irrigation scheme. For example, it may be difficult for the Agricultural Department to provide a greater than normal number of extension workers and a more intensive agricultural extension service within the irrigation scheme so that farmers can take advantage of the new opportunities.

Another disadvantage is that there is no co-ordinating mechanism in this structure. It is assumed that there are dynamic social groups who will ensure co-ordination through "bottom-up" forces, for example, farmers demanding adequate services.

As far as weed control is concerned, this lack of coordination means there is no centralised information on problem weeds in both channels and fields, and no coordination in use of equipment for maintenance and agricultural operations.

Attempts are sometimes made to overcome this problem through co-ordination committees with representatives from the different organisations. An example is the system of Irrigation Committees used in Sumatra, Indonesia (Helmi, 1996). However the constraints of the individual organisations may restrict the committee's effectiveness.

Segregated structures are common in large-scale irrigation and drainage schemes, for example, the Welland and Deepings Internal Drainage Board in UK. They are also found in small-scale irrigation schemes (such as Gem Rae in Kenya) where farmers, organisations concentrate on supply of water and outside agencies provide agricultural services. These schemes have been described in Chapter 2.

9.2.3 Integrated structure

In the integrated approach it is assumed that the overall goal can best be achieved by one organisation which co-ordinates a number of departments or sections, each concerned with the individual goals. Integrated organisations are therefore responsible for managing other activities as well as irrigation, for example:

- agricultural extension (e.g. advice on cropping practices)
- agricultural inputs (e.g. seed, chemicals, machinery)
- agricultural operations (e.g. on a state farm)
- agricultural credit
- community facilities (e.g. housing, water supply and sanitation, health, communications and transport etc.)
- collating information (e.g. list of aquatic needs)

Integrated management structures are used on state farms (for example, the Chisumbanje case study) and settlement schemes (for example, Mwea ISS). The organisational structure at Mwea ISS is shown in Figure 9.2.

The integrated structure has the advantage that it makes specific provision for the co-ordination of all the important aspects to achieve the various goals. In this way it can ensure that the farmers receive all the necessary services, such as extension, inputs and credit, to enable them to make use of the irrigation water. Particular services provided at Mwea ISS include mechanised land preparation and transport of the harvested rice.

The structure can be used to centralise information on a range of aspects, e.g. trials of new weed control measures on both agricultural fields and channels.

The disadvantage is the complexity of the resulting structure. For this reason the integrated structure is mostly found where farmers' conditions are fairly uniform, such as on settlement schemes, state farms and estates, and on schemes below about 10,000 ha in size.

Figure 9.1 A typical segregated organisational structure

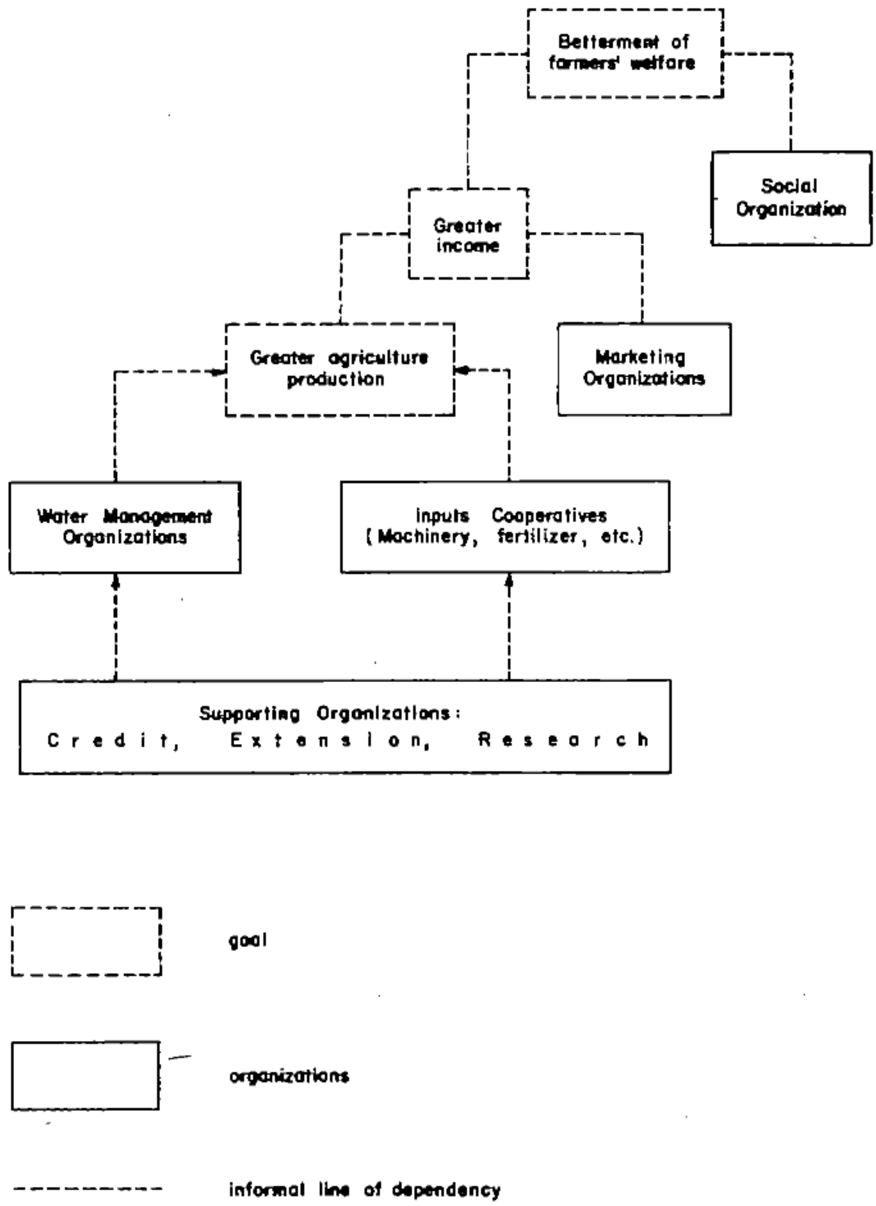
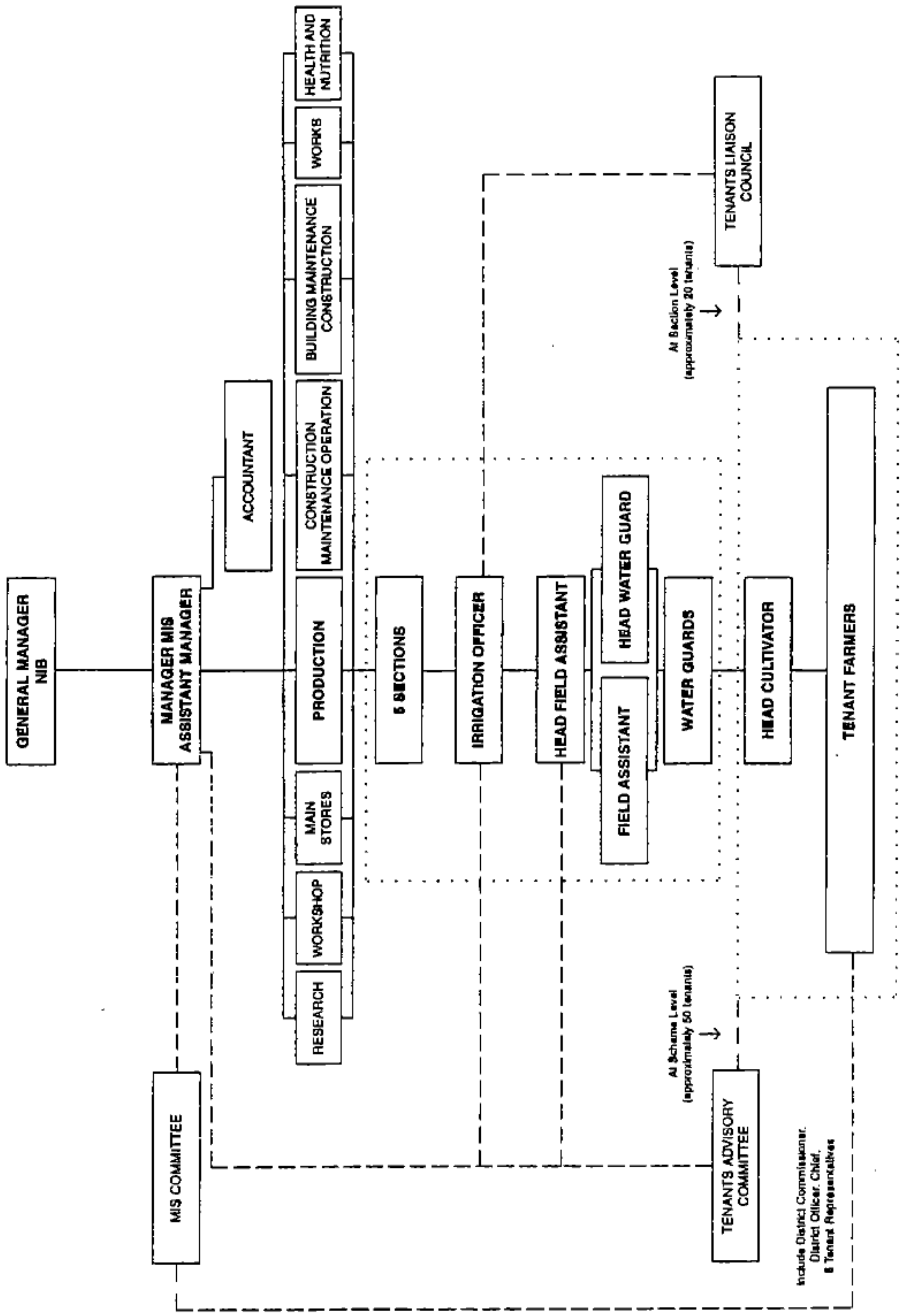


Figure 9.2 A typical integrated organisational structure - Mwea ISS



9.2.4 Project organisations

Projects are essentially investment activities undertaken over a particular time period. An organisation may be created to implement a project, but this is also limited to the duration of the project and is thus a temporary organisation, not a long term organisation.

Projects usually have specific goals which justify the investment, and as a result irrigation projects often include a range of components covering activities such as irrigation, agricultural extension, agricultural inputs, credit which are required to achieve the project goals. In some cases where these activities are normally undertaken by a number of segregated government agencies, integrated project organisations are set up to provide the concerted effort on the range of components without fragmentation between different line agencies. The project organisation may undertake all the activities directly, or may just provide co-ordination and attention to bottlenecks, leaving the implementation of the components to the line agencies.

9.2.5 Water User Associations

Water User Associations (WUAs) is a term used to describe organisations of the farmers in an irrigated area, for their own benefit. They are normally set up by government according to particular rules. The structure of WUAs may be based on one of the following:

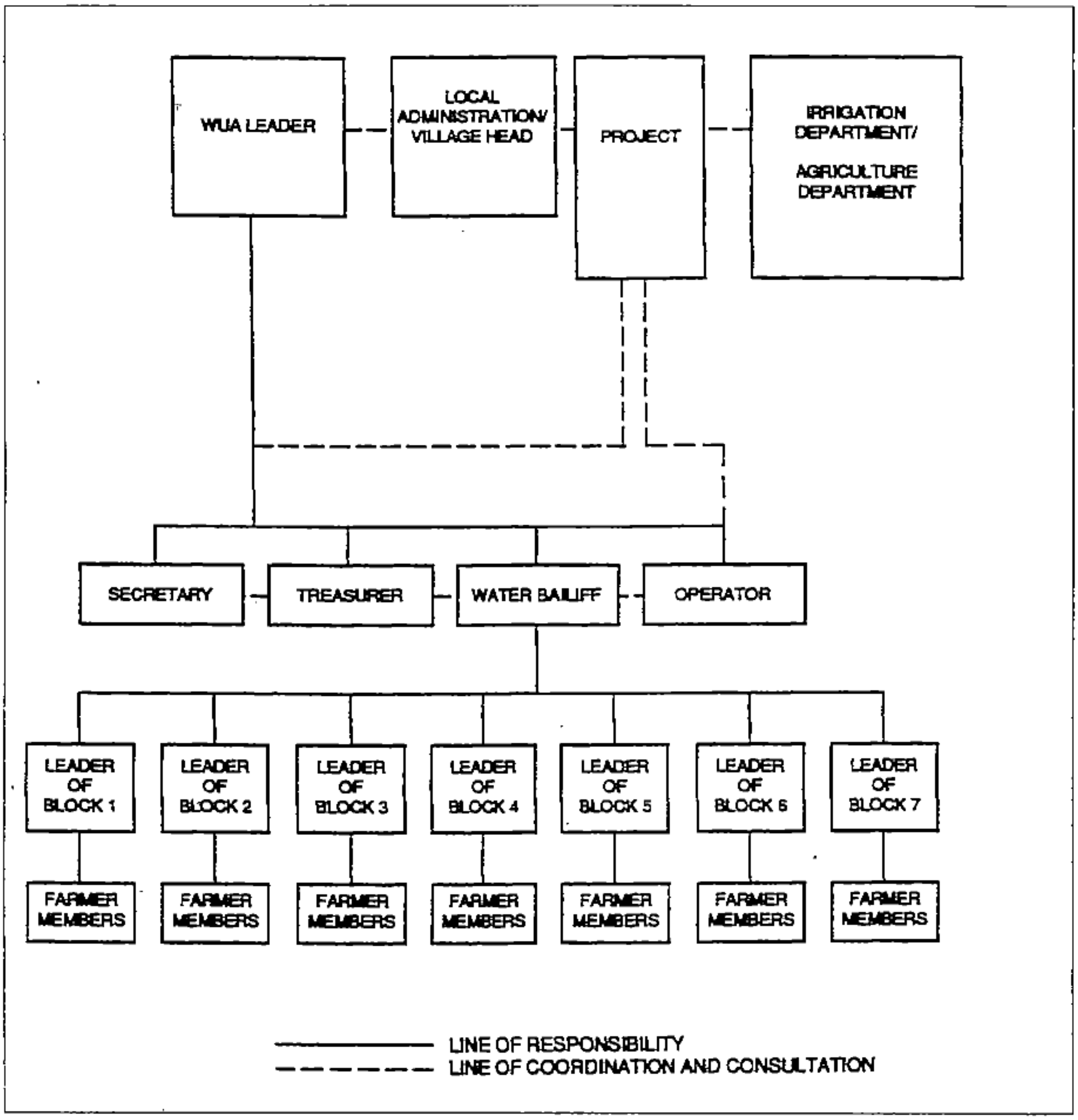
- social units (communities)
- local government units (official villages and districts)
- irrigation units (tertiaries, secondary canals)
- existing, usually informal, organisations.

For a simple small-scale irrigation system with a single tertiary canal, these units will commonly be the same. On larger systems, the standard and generally most effective organisational form for WUAs is based on irrigation or hydrological boundaries, so that the WUA can coordinate water supply and maintenance among the users.

WUAs are commonly based on tertiary canals and a typical WUA structure (for example, the Madura Groundwater Irrigation Project, Indonesia) is shown in Figure 9.3. In this example the WUA is primarily concerned with the distribution of water, maintenance of field channels and resolving conflicts between individual farmers. WUA activities vary from country to country, depending particularly on the limit of the irrigation agency's responsibility. The WUA can also have an important role in eliciting group decisions, for example on cropping, patterns and planting dates, and in providing two way communication between government and farmers, for example explaining, to farmers the purpose of the various irrigation structures and bringing farmers' problems to the attention of government staff.

The Gem Rae system is another example of the WUA structure (see Chapter 2).

Figure 9.3 A typical Water User Association (WUA) structure (from Madura Groundwater Irrigation Project, Indonesia)



9.3 Maintenance responsibilities

Policy issues were discussed in Chapter 5 (section 5.5). The government agency will usually be responsible for maintenance of the major canals and structures, down to a point (for example, the head of the tertiary canal, or the outlet to the farm) where responsibility is taken over by the farmers or a Water User Association.

9.3.1 Maintenance by government agency

This requires the following activities:

- systematic reporting of condition of canals, drains and structures
- systematic scheduling of work and budgeting
- regular servicing of pumpsets or other equipment
- emergency repairs following breakdown or damage
- servicing and repair of operation and maintenance equipment itself, e.g. by an efficient workshop
- surveillance for alien invasive aquatic weeds.

In canals and drains the important tasks are to clear sediment by labour or machine and weed by labour, machine, chemicals or biological methods. Such methods have been described in Chapter 4. Maintenance may be carried out while the canal is flowing or at fixed closure periods.

Maintenance of structures includes:

- measures to safeguard their structural stability, particularly maintaining earthworks and downstream protection to prevent by-passing or undercutting due to scour
- greasing and painting of water control structures (e.g. gates)
- attention to blockages, for example accumulation of weeds behind weirs and silt deposits in culvert pipes which would affect the structure's operation
- repair to leaking joints of concrete pipes, and repair of damage to structures.

On all types of scheme, maintenance is frequently neglected, leading to serious problems which eventually require a scheme to be rehabilitated. This neglect reflects the low priority given to maintenance, and consequent low budgets.

9.3.2 Maintenance by the water user association

The main problem here is that maintenance tasks and their importance are not always immediately apparent to farmers who may therefore neglect preventive maintenance on improved irrigation schemes, as tends to happen on other types of community development schemes. A strong effort is needed by government staff to overcome this, firstly by explaining the tasks, secondly by training someone to be responsible for ensuring that the tasks are carried out, and thirdly by checking from time to time that the scheme is being maintained properly.

Maintenance activities typically include the following:

- minor day-to-day reshaping and weeding of canals and structures to prevent blockages and leakage developing into more serious problems; these can be carried out by an agency employee (e.g. water guard) or farmers;
- repairs to canals and structures before each season as necessary, usually carried out by all the WUA members working together; some materials may need to be purchased, such as cement and paint (e.g. for water control gates);
- regular servicing of pumpsets or other equipment;
- emergency repairs following breakdown or damage.

These activities require diligence from the water guard and the mobilisation of labour by the WUA. The requirement for funds varies with the type of scheme and the responsibilities of the WUA, from simple gravity schemes which may occasionally need a bag of cement, to tubewell schemes which need funds on a daily basis for operation, with additional requirements from time-to-time for repairs.

Farmers are understandably reluctant to part with their money and suspicious about what will happen to it, so if funds are not needed regularly, it is unnecessary for the WUA to collect fees until the need arises or the WUA has built up trust among the farmers. However if funds are needed frequently it is important that systematic procedures are introduced for the WUA to follow, covering for example:

- agreeing a budget and water charge;
- collecting and keeping funds (e.g. in a WUA bank account);
- recording receipts and expenditures (e.g. in an official cash book);
- accounting for these publicly (e.g. by reading them out in the WUA meeting).

If farmers are satisfied about security of funds and the financial procedures, the WUA can aim to collect sufficient funds on a regular basis to build up a reserve for emergency maintenance.

9.4 Financing and cost recovery of operation and maintenance expenditure

Expenditures may be financed from government funds but it is usual for a direct contribution to be made by farmers paying water charges to the government or scheme management.

Experience shows that collection of these charges is very difficult. The farmers often regard it as another tax, and indeed the government often treats water charge payments as general government revenue, e.g. for administration by Ministry of Finance. Recent studies (Small and Carruthers, 1991) have concluded that it is important that payments for water are directly linked to operation and maintenance budgets, to improve incentives.

Governments generally find it very difficult to collect sufficient revenue from water charges to cover the operation and maintenance costs; as a result there is little chance of recovering any of the capital costs. However farmer participation (e.g. unpaid labour) can make a contribution to cost recovery by reducing direct operation and maintenance costs and by reducing direct construction costs, particularly at tertiary level.

Water charges may be set in one of the following ways, or a combination:

1. irrigation service fee
- area charge, where a charge is levied per hectare irrigated - this is a simple system, and land records can provide the basic data
- crop area charge, where a higher charge per area is levied for some crops (e.g. rice, which has higher water requirements)

2. water price
- volumetric charge, but this requires records of volume of water delivered
- time charge (e.g. in tubewell irrigation), requiring records of hours of supplied water

At Mwea ISS farmers pay an irrigation service fee through a crop charge at the time of harvest.

9.5 Data collection and monitoring

Monitoring refers to the systematic inspection of assets condition and the judging of their fitness to fulfil their intended functions. Monitoring should be ongoing and routine rather than an occasional and special event.

Routineness increases the probability of early identification of potential and actual sources of system failure. Early identification may allow relatively cheap and quick preventative maintenance rather than later expensive remedial work.

The success of monitoring condition may be enhanced by:

- the use of checklists requiring evaluation of asset condition
- the inculcation in all members of the workforce of the philosophy that timely preventive maintenance saves costly repairs
- the encouragement of inspection and reporting by all workers, perhaps supported by a reward system
- accumulation and collation of data on the aquatic weed communities
- data availability from which judgement can be made as to asset condition overtime
- provision of a reliable reporting mechanism to a responsive management.

Items to be monitored include:

- the type of weeds and their rates of growth
- the rate of silt build up
- the significance of weed and silt conditions for the hydraulic performance of the system
- the appearance of alien invasive water weeds
- the physical condition of machinery, canals and drains
- identification of weak spots
- regular, systematic measurements of discharges of canals and channels
- the productivity of workers, machines and management

Data collection should be selective and provide a resource to improve the management and planning of the maintenance programmes. It is particularly useful to develop time series on a monthly basis of resources required for programmes and a record of their costs.

The specific tasks upon which resources are deployed through time should be recorded e.g. maintaining canals, drains or roads. Each of these broad areas of work may be thought of as cost centres and can be broken down further into sub-costs e.g. main, secondary or tertiary canals.

For each cost centre and sub-centre the specific tasks on which resources are deployed should be recorded. On a monthly basis the split of labour and machine time is recorded showing the demand for inputs through time.

For each month the input costs associated with specific levels of input use should be recorded.

The purposes of this data collection exercise is to:

- identify when particular inputs e.g. excavator time or casual labour is most in demand
- aid the synchronisation of input use between tasks and locations
- suggest periods of especially heavy input demands and focus attention upon when economies in input use would be particularly rewarding
- illustrate the profile of costs through the agricultural year as an aid to budgeting
- provide the quantities and cost of inputs needed as ingredients for the calculation of annual machine costs and annual labour costs. These are main items in the calculation of annual maintenance costs in the Least Cost Analysis calculations.

Figures 5.3 and 5.4 in Chapter 5 give an example of the analysis of data in this way, to show canal maintenance and drain maintenance inputs by machine and by labour at Mwea ISS. It would be useful for management to break these down further into cost-centres for weeding and desilting, and to convert the inputs into costs. The effectiveness of the weeding and desilting operations could then be assessed, and compared with alternative methods.

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CHAPTER 10

CONCLUSION

10.1 Introduction

Two of the solutions promoted to satisfy the irrigation needs faced by a growing world population are the creation of new irrigation schemes and improving the efficiency of existing schemes. Observations of existing schemes both from first hand experience and through the literature have shown that the efficiency of irrigation systems is significantly reduced by aquatic weed growth in irrigation channels, drainage channels and in intermediate reservoirs. These guidelines develop an approach to dealing with this problem in a cost efficient way such that the efficiency of the scheme is overall improved, a contribution towards satisfying the irrigation needs of today and for tomorrow.

10.2 Aquatic weeds and their control

The impact of weed growth in channels is both direct, impeding water flow and hindering agricultural activity, and indirect, e.g. creating a habitat for the hosts of disease carrying snails and flies. The solution promoted here begins with developing an understanding of the aquatic weeds occurring in the channels. Identification of the offending species leads on to consideration of the most appropriate techniques for dealing with them. These guidelines have focused on manual control methods as the most widely used means of clearing weeds from channels.

There is a surprisingly wide range of tools which have been employed to cut, hoe and dig weeds although for any one scheme the range of tools being used is typically restricted to one or two techniques based very much on the tradition of that area. It is recommended that irrigation managers and farmers consider the wider range of tools and their applicability to the weed problems they encounter. Adding new tools to their armoury might not only improve weed clearing efficiency but also prevent laborers having to enter the water. This would reduce the likelihood of contracting water borne diseases.

Mechanical methods such as weed cutting buckets and weed boats might appear attractive but, apart from the initial cost, can pose problems in their maintenance and possibly more importantly the difficulty in making sure that they are well used throughout the cropping year. For this reason equipment which can be fitted onto existing tractors or excavators becomes more attractive from the economic viewpoint. Herbicides, too, have their limitations especially given the multiple use to which irrigation channels are put, e.g. drinking water and bathing. On the other hand, relative to mechanical methods, they can be cheap and particularly effective against certain types or species of weeds. Staff would need to be thoroughly trained in the use of chemicals for weed control in water, even those who are competent at using herbicides in the fields.

Biological control can be useful especially in the form of shading using trees or large leaved rooted floating species. These are best used as long term measures or built into new irrigation schemes in order to be of real value. Other biological agents such as herbivorous fish and insects are difficult to introduce at the scheme level but national projects could be of significant value for certain target species such as water hyacinth (*Eichhornia crassipes*) and water lettuce (*Pistia stratiotes*).

Environmental or integrated control can be valuable as an approach to aquatic weed control. It is unlikely that just one method of weed control will suffice for all the different types of weeds and channels and it is not a good idea to be reliant on a single approach. In reality, it is common to come across, for example, schemes managed using manual methods backed up by an excavator. More attention could be paid to the relationship between the methods of control and the success achieved in controlling the aquatic weeds. In effect, aquatic weed control is more to do with manipulating the ecology of the channel than specifically killing a particular type of weed or weeds. Cutting the weeds in a channel returns its ecology to an earlier stage in its development cycle, a development process which began after the last maintenance operation (Figures 3.2 and 3.3). dredging, for example, will return the ecology to the earliest stage in the cycle, whereas cutting will may be only push it back one stage.

Different channel types have different aquatic weed communities and these are one more reason for the need for different maintenance for different channel types. For example, primary irrigation channels need regular maintenance to keep them open and functioning efficiently. This creates a habitat suitable for submerged weeds which need to be cut by long handled scythes. A tertiary channel, however, is less critical in terms of function which, coupled with its smaller dimension means that it is suitable for emergent weed growth best managed using a slasher or hoe.

10.3 Relating weed growth to channel performance

In order to achieve efficient weed control, it is necessary to decide upon the level of service expected for each channel type. This level of service will tolerate a certain amount of weed growth depending upon channel type, but beyond that level of growth, the channel becomes inefficient and hence needs management. Irrigation managers and farmers should decide upon levels of service described both in engineering terms, e.g. freeboard, and weed terms, e.g. percentage weed cover of the channel which is acceptable for a given type of weed, such as 40% submerged weed and 10-20% emergent weed. The time at which assessments are made is important and should be related to the cropping cycle in that some channels will have a limited or no function at certain times of the year.

The level of service is not related to weed growth alone, and sediment accumulation is another important factor. This and other factors would need to be taken into consideration and the management might need to deal with silt accumulation and weed growth on some occasions whilst on others weed control alone might suffice.

10.4 Considering options

The guidelines promote an economic approach to determining the best option for weed management. This is based on describing the current modus operandi for the irrigation system and its associated costs extrapolated over a number of years. This exercise alone can be useful in determining where money is being spent and more importantly ways of working more efficiently, e.g. wiser use of labour. Current practice should then be compared with other management strategy options which have been drawn up for the scheme. These might be variations on the current regime or they might introduce new methods of manual control or include the purchase of a machine for mechanical control. Such options need to be costed out carefully and again compared with current management over a number of years. The time factor is very important and a period of about 15 years is recommended.

The evaluation of management strategy options is initially time consuming as there is much data to collect on such factors as length of time it takes to maintain a stretch of tertiary channel and the annual maintenance costs for a mechanical excavator. After the first time, however, most of the data will remain much the same and the process becomes easier and quicker. Considering new options and monitoring the progress of implemented options becomes part of the overall system management.

The examples presented in these guidelines emphasise the need to deal with the economic factors in appropriate detail, e.g. including the need to write off capital purchases over time and the depreciation of assets.

10.5 Policy implications for planners and decision makers

The management of an irrigation system is governed in large measure by institutional factors. These need to foster the approach described in these guidelines, namely the acquisition of information relating to current weed maintenance and consideration of alternatives. On the basis of the outcome of such decision making, the institution needs to be able to implement those decisions and to appraise there success or otherwise over time.

The general existence of tight budgets strengthens the requirement for a systematic approach to maintenance. This requires an understanding of the necessary condition of assets to deliver a particular standard of performance and the identification of inputs and associated costs to meet that standard. Above all, maintenance should be viewed as a long term planned activity.

A strong and direct link between payment and service provision is likely to improve payment compliance and collection, And also farmer cooperation in maintenance programmes. These factors improve the prospects for cost recovery and a more hydraulically efficient and productive system.

There is a need to train staff at the scheme level to describe weed communities using the descriptive system referred to in Chapter 3, and to recognise the main species of plants, and then to plan weed management on the basis of species and ecology rather than tradition and expediency.

Projects for new and rehabilitated irrigation schemes provide opportunities to establish systematic maintenance procedures which integrate engineering, economic and ecological perspectives, as developed in this research. These procedures should prevent the establishment of undesirable species within the channels. The possible need for access of maintenance machinery also needs to be considered when designing the channels.

APPENDIX 1

Table A1.1 - Aquatic Weeds Recorded in Irrigation and Drainage Systems in Africa.

Scientific Name and Authority	Common Name	Habit
Abutilon guineense (Schumach.) Bak. & Exell		E
Acmella caulorhiza Delile		
Ageratum conyzoides		
Ajuga remota		
Alternanthera sessilis (L.) DC	Alternanthera	E
Alysicarpus rugosus		
Amaranthus hybridus L.	Smooth pigweed	E
Amaranthus spinosa		
***Ammania coccinea* Rottb.**	**Water amaranth**	E
Aponogeton abyssinicus		
Asystasia		
Azolla Lam.	Water-velvet	FF
***Azolla caroliniana* Willdenow**	**Mosquito fern**	**FF**
***Azolla pinnata* R.Br**	**Fairy moss**	**FF**
Basilicum polystachyon (L.) Moench.	Wild basil	
Bidens biternata		
Bidens pilosa		
Bothriochloa insculptum		
***Brachiaria mutica* (Forsk.) Stapf**	**Para grass**	**E/RF**
Centella asiatica		
Ceratophyllum demersum L.	Coontail	S
***Chara* L.**	**Stonewort**	**A**
***Chara contraria* A. Braun ex Kutz.**	**Stonewort**	**A**
***Chara globularis* Thuill.**	**Stonewort**	**A**
Chloris pycnothrix		
Commelina	Day flower	E
Commelina diffusa		
Conyza albida		
Corchorus asplenifolius		
Corchorus olitorius	Jew's mallow; jute	
Corchorus trilocularis		
Cynodon dactylon (L.) Pers.	Bermuda grass; couch; quick grass; star grass	E
Cyperus articulatus	Chintul	E
Cyperus difformis L.	Rice sedge	E
Cyperus digitatus Roxb. ssp. *auricomus* Spreng.		
Cyperus distans L.f.		
Cyperus dives		
Cyperus esculentus		
Cyperus involucratus		
Cyperus longus		
Cyperus papyrus L.	Papyrus	E
Cyperus rotundus	Nut grass	E
Datura stramonium		
Desmodium		
Dichanthium		
Digitaria		
Dinebra retroflexa (Vahl) Panzer	Cat's tail grass	
Dyschoriste		
Echinocloa L.	Wild millet	E

Echinochloa colona (L.) Link	Barnyard grass; jungle rice grass	
Echinocloa crus-galli **(L.) Beauv.**	**Barnyard grass**	**E**
Echinocloa haploclada	**Wild millet**	**E**
Echinochloa jubata Stapf		
Echinochloa pyramidalis		
Echinocloa stagnina Retz. Beauv.	Watergrass	E
Eclipta alba (L.) Hassk.		
Eichhornia azurea (Sw.) Kunth.	Rooted water hyacinth	RF
Eichhornia crassipes (Mart.) Solms.	Water hyacinth	FF
Elatine triandra **Schkruhr**	**Waterwort**	**S/E**
Eleocharis **R.Br.**	**Spike rush**	**S/E**
Eleocharis dulcis **(Burm. f) Henschel**	**Spike rush**	**E**
Eleocharis palustris **(L.) Roemer & Schultes**	**Common spike rush**	**S/E**
Eragrostis N.M. Wolf	Lovegrass	
Eriochloa Kunth		
Erythrochlamys spectabilis		
Euphorbia heterophylla L.		
Euphorbia hirta L.	Asthma weed	
Euphorbia indica		
Euphorbia inequilatera		
Euphorbia serpens Kunth		
Fimbristylis bisumbellata		E
Fimbristylis dichotoma		
Fimbristylis ferruginea		
Fimbristylis miliacea **(L.) Vahl.**	**Fringe rush**	**E**
Fluchea bequertii		
Galinsoga parviflora		
Hemarthria altissima		
Heteranthera limosa **(Schwartz.) Willd.**	**Longleaf mudplantain**	**E**
Heteranthera reniformis **Ruiz & Pavon**	**Round leaf mudplantain**	**E/RF**
Heteranthera rotundifolia	**Mud plantain**	
Indigofera parviflora		
Ipomoea aquatica (Forsk.)	Water spinach	RF
Ipomoea cairica		
Isachne	Isachne	E
Ischaemum afrum		
Kyllinga		
Launaea cornuta		
Leersia oryzoides **(L.) Swartz.**	**Rice cut-grass**	**E**
Leersia hexandra		
Lemna L.	Duckweed	FF
Lemna gibba L.	Fat duckweed	FF
Lemna minor L. agg	Lesser duckweed	FF
Lemna perpusilla **Torr.**	**Duckweed**	**FF**
Lindernia dubia	**False pimpernel**	**E**
Ludwigia L.	False loosestrife	RF
Ludwigia abyssinica		
Ludwigia decurrens Walt.	Water primrose	
Ludwigia jussiaeoides		
Ludwigia octovalvis		
Ludwigia repens Forst	Water primrose	S/E/FF
Ludwigia stolonifera (Guill. & Perr.) Raven	Creeping water primrose	
Ludwigia uruguayensis **(Cambess.) Hara**	**Water primrose**	**E**
Lythrum rotundifolium		
Marsilea		
Mimulus gracilis R. Br		
Monochoria elata	Monochoria	E
Monochoria korsakowii **Regal & Maack**	**Monochoria**	**E**
Myriophyllum aquaticum **(Vell.) Verd.**	**Parrotfeather**	**S/E**
Myriophyllum brasiliense **Cambess.**		

Myriophyllum spicatum L.	Spiked water milfoil	S
Myriophyllum exalbescens Fern.		
***Myriophyllum verticillatum* L.**	**Whorled water-milfoil**	**S**
Najas horrida A. Braun ex Magnus	Niaid	S
***Najas guadalupensis* (Spreng.) Magnus**	**Southern naiad**	**S**
Najas marina L.	Holly-leaved niaid	S
***Najas minor* All.**	**Brittle naiad**	**S**
Nesaea Commers.		
Nidorella resedifolia		
***Nitella* (C.A. Agardh.) Leonhardi**	**Stonewort**	**A**
***Nuphar lutea* L. Sm.**	**Yellow waterlily**	**RF**
***Nuphar luteum* Sibth. & Small**	**Spatterdock**	**RF**
***Nymphaea* L.**	**Water lily**	**RF**
***Nymphaea alba* L.**	**White waterlily**	**RF**
***Nymphaea coerulea* Savigny**	**Water lily**	**RF**
***Nymphaea lotus* L., non Hook. f. & Thoms.**	**Water lily**	**RF**
***Nymphaea odorata* Ait.**	**Fragrant water lily**	**RF**
***Nymphoides indica* (L.) O. Kuntze**	**Water snowflake**	**RF**
***Nymphoides peltata* (S.G. Gmel.) O. Kuntze**	**Fringed waterlily**	**RF**
Ottelia alismoides (L.) Pers.	Turtle grass	S
Ottelia exerta		
Oxalis		
Oxygonum sinuatum		
Panicum repens L.	Torpedo grass	E
***Paspalum distichum* L.**	**Knotgrass**	**E**
Paspalum pasploides		
Paspalum scrobiculatum L.	Creeping paspalum; kodo millet	
Persicaria decipiens (R. Br.) K.L. Wilson		
Persicaria senegalensis (Meisn.) Sojak		
Phragmites australis (Cav.) Trin. ex Steudal	Common reed	E
Phragmites communis Trin.		
Phyllanthus maderaspatensis		
Pistia stratiotes L.	Water lettuce	FF
Polygonum amphibium L.	Amphibious bistort	RF
Polygonum hydropiper (L.) Spach	Water-pepper	E
Polygonum persicaria L.	Redshank	E
Polygonum pulchrum		
Polygonum salicifolium		
Portulaca oleracea		
***Potamogeton amplifolius* Tuckerman**	**Large-leaved pondweed**	**S**
Potamogeton crispus L.	Curled pondweed	S
***Potamogeton foliosus* Raf.**	**Leafy pondweed**	**S**
***Potamogeton gramineus* L.**	**Various-leaved pondweed**	**S**
***Potamogeton illinoensis* Morong**	**Illinois pondweed**	**S**
Potamogeton nodosus Poir.	Loddon pondweed	S/RF
Potamogeton pectinatus L.	Sago pondweed	S
Potamogeton perfoliatus L.	Perfoliate pondweed	S
***Potamogeton praelongus* Wulfen**	**Long-stalked pondweed**	**S**
***Potamogeton pusillus* L.**	**Lesser pondweed**	**S**
***Potamogeton richardsonii* (Benn.) Rydb.**	**Clasping-leaved pondweed**	**S**
***Potamogeton tricarinatus* F. Muell. & A. Benn, ex A. Benn**	**Floating pondweed**	**S/RF**
Potamogeton trichoides Cham. & Schlecht.	Hair-like pondweed	S
Pycnostachys deflexifolia		
Pycreus polystachyos		
Rhynchosia holstii		
Rottboellia cochinchinensis (Lour.) W.D. Clayton	Guinea-fowl grass; itch grass	
Salvinia Seguier	Salvinia	FF
***Salvinia cucullata* Roxb.**	**Water spangle**	**FF**
Salvinia molesta D.S. Mitchell	Kariba weed	FF
Schoenoplectus		

Scirpus L.	Bulrush	E
Sesbania		
Setaria		
Sida cuneifolia		
Sida rhombifolia		
Solanum incanum		
Solanum nigrum		
Sonchus		
Sorghum arundinaceum		
Sphaeranthus cyanthuloides		
Sporobolus		
Stenotaphrum secundatum (Walt.)	Buffalo grass	
Typha L.	Cattail	E
Typha angustata Bory & Chaub.	Cattail	E
Typha angustifolia L.	Narrowleaf cattail	E
Typha domingensis Pers.	Southern cattail	E
Typha latifolia L.	Common cattail	E
***Vallisneria americana* Michx.**	**Eelgrass**	**S**
***Vallisneria spiralis* L.**	**Ribbon-weed**	**S**
Vernonia glabra		
Vigna oblongifolia		
Vossia cuspidata (Roxb.) Griff.	Hippo grass	E
Zannichellia palustris L.	Horned pondweed	S

A = alga; E = emergent; FF = free-floating; FL = floating-leaves; S = submerged.

Table A1.2 Noxious weeds in irrigation and drainage channels in Africa.

Scientific Name and Authority	Common Name	Status
Azolla Lam.	Water-velvet	
Cyperus papyrus L.	Papyrus	N
Echinochloa sp.	Wild millet	N
Eichhornia crassipes (Mart.) Solms.	Water hyacinth	E
Leersia hexandra		N
Panicum repens L.	Torpedo grass	N
Pistia stratiotes L.	Water lettuce	N
Salvinia molesta D.S. Mitchell	Kariba weed	N
Typha domingensis Pers.	Southern cattail	N
Vossia cuspidata (Roxb.) Griff.	Hippo grass	N

E = exotic species; N = native species.

Table A1.3 Uses for aquatic weeds occurring in irrigation and drainage systems in Africa.

Species	**Uses**
Acmella caulorhiza	Kenya: crushed plant is applied to broken limbs. West Africa: used for medicinal purposes.
Ageratum conyzoides	Kenya: juice is used to stop bleeding, to treat sore eyes and bowel complaints. West Africa: used for medicinal purposes.
Ajuga remota	Kenya: used as a cure for malaria.
Alternanthera sessilis	Kenya: used a soil addititve; leaves are used as famine food and as fodder during drought periods.
Amaranthus hybridus	Asia and America: occasionally grown as a grain crop. Zimbabwe: leaves are used as spinach; whole plant is sometimes burnt and the ash mixed with snuff or used in place of salt when cooking other leaves.
Bidens biternata	Zimbabwe: young shoots and leaves are cooked as a relish; plant is used for medicinal purposes.
Bidens pilosa	Kenya: used as a cure for diarrhoea in suckling babies.
Commelina sp.	Kenya: leaves are used as a vegetable; plant also used as a fodder and as a soil additive.
Corchorus asplenifolius	Zimbabwe: leaves are cooked as a relish.
Corchorus olitorius	Asia: plant is grown commercially for fibre. Kenya and Zimbabwe: leaves are cooked as a relish; stem is used as fibre.
Cynodon dactylon	Zimbabwe: used for lawns and sportsfields, bank stabilisation and waterway protection; also provides good grazing.
Cyperus digitatus	Zimbabwe: stems are used for weaving mats and baskets and also as a thatching material.
Cyperus dives	Kenya: leaves are used as a thatching material, as fodder and as a soil additive.
Cyperus esculentus	Kenya: dried tubers are used as ornamental beads. Southern and central Europe: plant is grown commercially for the edible tubers (tiger nuts). Zimbabwe: new tubers are chewed raw or cooked as vegetables; after roasting and grinding they may be used as a coffee substitute; plant is a source of potash for softening and flavouring green leaves.
Cyperus involucratus	Zimbabwe: root is prepared for potash; stems are used for weaving mats.
Cyperus latifolius	Kenya: leaves are used as a hatching material, as fodder and as a soil additive; plant is a source of potash for softening and flavouring green leaves.
Cyperus rotundus	China: the plant is used in traditional medicine. Kenya: dried tubers are used as ornamental beads.
Echinochloa colona	Zimbabwe: seeds are sometimes collected and ground into flour.
Euphorbia heterophylla	East Africa and Malaya: plant is used in traditional medicine.

Euphorbia hirta	Britain, India and West Africa: plant is used for medicinal purposes.
Imperata cylindrica	Kenya: plant is used as a thatching material.
Lantana camara	Kenya: ashes from burned leaves and salt are used to treat coughs, sore throats conjunctivitis and toothache.
Leersia hexandra	Kenya: leaves and sand are used for cleaning calabashes; plant is also used as fodder and as a soil additive.
Ludwigia stolonifera	Kenya: plant is used as a soil additive.
Paspalum scrobiculatum	India: improved strains are cultivated for grain and fodder as Kodo millet.
Phragmites mauritiana	Kenya: plant is used in house construction.
Portulaca oleracea	Europe: young shoots are eaten as a salad vegetable. Zimbabwe: plant is sometimes cooked as a relish. Plant is, or was, used as a pot-herb and a medicinal herb in many countries.
Ricinus communis	Kenya: stems are used for firewood. Castor oil, extracted from plant, is used in many countries.
Rottboellia cochinchinensis	Zimbabwe: grain is used as famine food.
Schoenoplectus sp.	Kenya: plant is used as fodder and as a soil additive.
Solanum incanum	Kenya: juice from the roots is used as a remedy for abdominal pains.
Solanum nigrum	Kenya: leaves are used as a vegetable and ground into a powder for treatment of burns and scolds. Zimbabwe: black, mature fruits are used in jam-making; leaves are cooked as relish; plant is used for medicinal purposes.
Sonchus oleraceus	Europe: young shoots are sometimes used in salads. Kenya: plant is used as rabbit food. Malawi and Zimbabwe: leaves are occasionally cooked as a vegetable.
Typha latifolia	Kenya: used for ornamental purposes, as bedding material and as fodder. Zimbabwe: all parts of plant may be used differently as famine food; plant may be burnt and used for salt substitute.

Table A2.1 **PRESENT VALUE OF £1**

Years Hence	4%	5%	6%	8%	10%	12%	14%	15%	16%	18%	20%	22%	24%	25%	26%	28%	30%	35%	40%
1	0.962	0.952	0.943	0.926	0.909	0.893	0.877	0.870	0.862	0.847	0.833	0.820	0.806	0.800	0.794	0.781	0.769	0.741	0.714
2	0.925	0.907	0.890	0.857	0.826	0.797	0.769	0.756	0.743	0.718	0.694	0.672	0.650	0.640	0.630	0.610	0.592	0.549	0.510
3	0.889	0.864	0.840	0.794	0.751	0.712	0.675	0.658	0.641	0.609	0.579	0.551	0.524	0.512	0.500	0.477	0.455	0.406	0.364
4	0.855	0.823	0.792	0.735	0.683	0.636	0.592	0.572	0.552	0.516	0.482	0.451	0.423	0.410	0.397	0.373	0.350	0.301	0.260
5	0.822	0.784	0.747	0.681	0.621	0.567	0.519	0.497	0.476	0.437	0.402	0.370	0.341	0.328	0.315	0.291	0.269	0.223	0.186
6	0.790	0.746	0.705	0.630	0.564	0.507	0.456	0.432	0.410	0.370	0.335	0.303	0.275	0.262	0.250	0.227	0.207	0.165	0.133
7	0.760	0.711	0.665	0.583	0.513	0.452	0.400	0.376	0.354	0.314	0.279	0.249	0.222	0.210	0.198	0.178	0.159	0.122	0.095
8	0.731	0.677	0.627	0.540	0.467	0.404	0.351	0.327	0.305	0.266	0.233	0.204	0.179	0.168	0.157	0.139	0.123	0.091	0.068
9	0.703	0.645	0.592	0.500	0.424	0.361	0.308	0.284	0.263	0.225	0.194	0.167	0.144	0.134	0.125	0.108	0.094	0.067	0.048
10	0.676	0.614	0.558	0.463	0.386	0.322	0.270	0.247	0.227	0.191	0.162	0.137	0.116	0.107	0.099	0.085	0.073	0.050	0.035
11	0.650	0.585	0.527	0.429	0.350	0.287	0.237	0.215	0.195	0.162	0.135	0.112	0.094	0.086	0.079	0.066	0.056	0.037	0.025
12	0.625	0.557	0.497	0.397	0.319	0.257	0.208	0.187	0.168	0.137	0.112	0.092	0.076	0.069	0.062	0.052	0.043	0.027	0.018
13	0.601	0.530	0.469	0.368	0.290	0.229	0.182	0.163	0.145	0.116	0.093	0.075	0.061	0.055	0.050	0.040	0.033	0.020	0.013
14	0.577	0.505	0.442	0.340	0.263	0.205	0.160	0.141	0.125	0.099	0.078	0.062	0.049	0.044	0.039	0.032	0.025	0.015	0.009
15	0.555	0.481	0.417	0.315	0.239	0.183	0.140	0.123	0.108	0.084	0.065	0.051	0.040	0.035	0.031	0.025	0.020	0.011	0.006
16	0.534	0.458	0.394	0.292	0.218	0.163	0.123	0.107	0.093	0.071	0.054	0.042	0.032	0.028	0.025	0.019	0.015	0.008	0.005
17	0.513	0.436	0.371	0.270	0.198	0.146	0.108	0.093	0.080	0.060	0.045	0.034	0.026	0.023	0.020	0.015	0.012	0.006	0.003
18	0.494	0.416	0.350	0.250	0.180	0.130	0.095	0.081	0.069	0.051	0.038	0.028	0.021	0.018	0.016	0.012	0.009	0.005	0.002
19	0.475	0.396	0.331	0.232	0.164	0.116	0.083	0.070	0.060	0.043	0.031	0.023	0.017	0.014	0.012	0.009	0.007	0.003	0.002
20	0.456	0.377	0.312	0.215	0.149	0.104	0.073	0.061	0.051	0.037	0.026	0.019	0.014	0.012	0.010	0.007	0.005	0.002	0.001
21	0.439	0.359	0.294	0.199	0.135	0.093	0.064	0.053	0.044	0.031	0.022	0.015	0.011	0.009	0.008	0.006	0.004	0.002	0.001
22	0.422	0.342	0.278	0.184	0.123	0.083	0.056	0.046	0.038	0.026	0.018	0.013	0.009	0.007	0.006	0.004	0.003	0.001	0.001
23	0.406	0.326	0.262	0.170	0.112	0.074	0.049	0.040	0.033	0.022	0.015	0.010	0.007	0.006	0.005	0.003	0.002	0.001	-
24	0.390	0.310	0.247	0.158	0.102	0.066	0.043	0.035	0.028	0.019	0.013	0.008	0.006	0.005	0.004	0.003	0.002	0.001	-
25	0.375	0.295	0.233	0.146	0.092	0.059	0.038	0.030	0.024	0.016	0.010	0.007	0.005	0.004	0.003	0.002	0.001	0.001	-
26	0.361	0.281	0.220	0.135	0.084	0.053	0.033	0.026	0.021	0.014	0.009	0.006	0.004	0.003	0.002	0.002	0.001	-	-
27	0.347	0.268	0.207	0.125	0.076	0.047	0.029	0.023	0.018	0.011	0.007	0.005	0.003	0.002	0.002	0.001	0.001	-	-
28	0.333	0.255	0.196	0.116	0.069	0.042	0.026	0.020	0.016	0.010	0.006	0.004	0.002	0.002	0.002	0.001	0.001	-	-
29	0.321	0.243	0.185	0.107	0.063	0.037	0.022	0.017	0.014	0.008	0.005	0.003	0.002	0.002	0.002	0.001	0.001	-	-
30	0.308	0.231	0.174	0.099	0.057	0.033	0.020	0.015	0.012	0.007	0.004	0.003	0.002	0.001	0.001	0.001	-	-	-
35	0.253	0.181	0.130	0.068	0.036	0.019	0.010	0.008	0.006	0.003	0.002	0.001	0.001	-	-	-	-	-	-
40	0.208	0.142	0.097	0.046	0.022	0.011	0.005	0.004	0.003	0.001	0.001	-	-	-	-	-	-	-	-
45	0.171	0.111	0.073	0.031	0.014	0.006	0.003	0.002	0.001	0.001	-	-	-	-	-	-	-	-	-
50	0.141	0.087	0.054	0.021	0.009	0.003	0.001	0.001	0.001	-	-	-	-	-	-	-	-	-	-

Table A2.2 **CAPITAL RECOVERY FACTORS**
(PERIODIC PAYMENT UNDER AN ANNUITY OF N PAYMENTS, PRESENT VALUE OF WHICH IS £1, ONE PERIOD BEFORE THE FIRST PAYMENT)

N	5%	6%	8%	10%	12%	14%	15%	16%	18%	20%	22%	24%	25%	30%	N
1	1.050	1.060	1.080	1.100	1.120	1.140	1.150	1.160	1.180	1.200	1.220	1.240	1.250	1.300	1
2	0.538	0.545	0.561	0.576	0.592	0.607	0.615	0.623	0.639	0.655	0.670	0.686	0.694	0.735	2
3	0.367	0.374	0.388	0.402	0.416	0.431	0.438	0.445	0.460	0.475	0.490	0.505	0.512	0.551	3
4	0.282	0.289	0.302	0.315	0.329	0.343	0.350	0.357	0.372	0.386	0.401	0.416	0.423	0.462	4
5	0.231	0.237	0.250	0.264	0.277	0.291	0.298	0.305	0.320	0.334	0.349	0.364	0.372	0.411	5
6	0.197	0.203	0.216	0.230	0.243	0.257	0.264	0.271	0.286	0.301	0.316	0.331	0.339	0.378	6
7	0.173	0.179	0.192	0.205	0.219	0.233	0.240	0.248	0.262	0.277	0.293	0.308	0.316	0.357	7
8	0.155	0.161	0.174	0.187	0.201	0.216	0.223	0.230	0.245	0.261	0.276	0.292	0.300	0.342	8
9	0.141	0.147	0.160	0.174	0.188	0.202	0.210	0.217	0.232	0.248	0.264	0.280	0.289	0.331	9
10	0.130	0.136	0.149	0.163	0.177	0.192	0.199	0.207	0.223	0.239	0.255	0.272	0.280	0.323	10
11	0.120	0.127	0.140	0.154	0.168	0.183	0.191	0.199	0.215	0.231	0.248	0.265	0.273	0.318	11
12	0.113	0.119	0.133	0.147	0.161	0.177	0.184	0.192	0.209	0.225	0.242	0.260	0.268	0.313	12
13	0.106	0.113	0.127	0.141	0.156	0.171	0.179	0.187	0.204	0.221	0.238	0.256	0.265	0.310	13
14	0.101	0.108	0.121	0.136	0.151	0.167	0.175	0.183	0.200	0.217	0.234	0.252	0.262	0.308	14
15	0.096	0.103	0.117	0.131	0.147	0.163	0.171	0.179	0.196	0.214	0.232	0.250	0.259	0.306	15
16	0.092	0.099	0.113	0.128	0.143	0.160	0.168	0.176	0.194	0.211	0.230	0.248	0.257	0.305	16
17	0.089	0.095	0.110	0.125	0.140	0.157	0.165	0.174	0.191	0.209	0.228	0.246	0.256	0.304	17
18	0.086	0.092	0.107	0.122	0.138	0.155	0.163	0.172	0.190	0.208	0.226	0.245	0.255	0.303	18
19	0.083	0.090	0.104	0.120	0.136	0.153	0.161	0.170	0.188	0.206	0.225	0.244	0.254	0.302	19
20	0.080	0.087	0.102	0.117	0.134	0.151	0.160	0.169	0.187	0.205	0.224	0.243	0.253	0.302	20
21	0.078	0.085	0.100	0.116	0.132	0.150	0.158	0.167	0.186	0.204	0.223	0.243	0.252	0.301	21
22	0.076	0.083	0.098	0.114	0.131	0.148	0.157	0.166	0.185	0.204	0.223	0.242	0.252	0.301	22
23	0.074	0.081	0.096	0.113	0.130	0.147	0.156	0.165	0.184	0.203	0.222	0.242	0.251	0.301	23
24	0.072	0.080	0.095	0.111	0.128	0.146	0.155	0.165	0.183	0.203	0.222	0.241	0.251	0.301	24
25	0.071	0.078	0.094	0.110	0.127	0.145	0.155	0.164	0.183	0.202	0.222	0.241	0.251	0.300	25
26	0.070	0.077	0.093	0.109	0.127	0.145	0.154	0.163	0.182	0.202	0.221	0.241	0.251	0.300	26
27	0.068	0.076	0.091	0.108	0.126	0.144	0.154	0.163	0.182	0.201	0.221	0.241	0.251	0.300	27
28	0.067	0.075	0.090	0.107	0.125	0.144	0.153	0.163	0.182	0.201	0.221	0.241	0.250	0.300	28
29	0.066	0.074	0.090	0.107	0.125	0.143	0.153	0.162	0.181	0.201	0.221	0.240	0.250	0.300	29
30	0.065	0.073	0.089	0.106	0.124	0.143	0.152	0.162	0.181	0.201	0.221	0.240	0.250	0.300	30

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These guidelines are the result of two years research undertaken by WEDC with collaborators in Zimbabwe and Kenya. They provide a systematic and interdisciplinary approach to the problems caused by aquatic weeds within irrigation and drainage systems in tropical and subtropical areas. This covers identifying the weeds growing in the channels, considering appropriate control options to provide an acceptable level of service, and drawing up a feasible, costed maintenance programme which can be implemented by the responsible institution. Various control methods are discussed: the use of hand tools and mechanical equipment, chemical and biological techniques, and environmental measures.

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